# SCIENTIFIC DESIGN FOR THE COMMON MODULE OF THE GLOBAL OCEAN OBSERVING SYSTEM AND THE GLOBAL CLIMATE OBSERVING SYSTEM:

# AN OCEAN OBSERVING SYSTEM FOR CLIMATE

Final Report of

The Ocean Observing System
Development Panel

March 1995

# Ocean Observing System Development Panel

**Dr. Michael McPhaden (NOAA/PMEL)**
**Dr. Liliane Merlivat (Université Pierre et Marie Curie)**
**Dr. George Needler (Bedford Institute of Oceanography)**
**Dr. Worth D. Nowlin, Jr. (Texas A&M University), Chairman**
**Dr. Raymond W. Schmitt (Woods Hole Oceanographic Institution)**
**Dr. Neville Smith (Bureau of Meteorology Research Centre)**
**Dr. Peter K. Taylor (James Rennell Centre for Ocean Circulation)**
**Dr. Alain F. Vézina (Universite du Quebec a Rimouski)**
**Dr. Masaaki Wakatsuchi (Hokkaido University)**
**Dr. Robert Weller (Woods Hole Oceanographic Institution)**
**Mr. Arthur Alexiou (Staff Scientist to the Panel from IOC)**

This report may be cited as:

The Ocean Observing System Development Panel. 1995. Scientific Design for the Common Module of the Global Ocean Observing System and the Global Climate Observing System: An Ocean Observing System for Climate. Department of Oceanography, Texas A&M University, College Station, Texas, 265 pp.

Copies of this report may be obtained from Dr. Worth D. Nowlin, Jr., Department of Oceanography, Texas A&M University, College Station, Texas 77843-3146; fax: (409) 845-0888.

# Scientific Design for the Common Module of the Global Ocean Observing System and the Global Climate Observing System:

# An Ocean Observing System for Climate

Final Report of

The Ocean Observing System Development Panel

# FOREWORD FROM GOOS AND GCOS

Oceanographers have long recognized the value of an ongoing operational observing system which would provide fundamental measurements to meet the observational needs of many user communities. Fortunately in recent years, several important steps have been taken to initiate plans for such a system. These plans culminated in agreements reached by IOC, WMO, UNEP, and ICSU to jointly sponsor a Global Ocean Observing System (GOOS). A fully developed GOOS will satisfy ocean observing requirements for climate monitoring, assessment and prediction, for monitoring and assessment of marine living resources and of the health of the ocean, for monitoring of the coastal zone environment and its changes, and for meteorological and oceanographic operational services.

To assist in developing the systematic observing requirements for the climate component of GOOS, as well as the requirements for the World Climate Research Programme (WCRP), the Ocean Observing System Development Panel (OOSDP) was established under the Joint Scientific committee and the Committee for Climatic Changes and the Ocean. It was charged to formulate a conceptual design for a long-term, systematic observing system to monitor, describe, and understand the physical and biogeochemical processes hat determine ocean circulation and the effects of the ocean on seasonal to decadal climate changes and to provide the observations needed for climate predictions.

To provide additional context for the work of the OOSDP, the Second World Climate Conference recommended a Global Climate Observing System (GCOS) be established to specifically address the observational needs for climate-related purposes including monitoring climate, detecting climate change and its impact, and supporting research toward understanding and prediction. When GCOS was envisioned it was acknowledged that a key ingredient must be a comprehensive ocean component and it was agreed that this component should be provided primarily through GOOS.

In 1992, the UN Conference on Environment and Development, in its Agenda 21, endorsed the concept of GOOS, and encouraged countries to support GCOS and related climate programs.

Since their establishment, both GOOS and GCOS have collaborated in the planning, development, and implementation of the ocean observing system for climate which will be the climate module of GOOS and the ocean component of GCOS. Similarly, both have looked to the oceanographic community through the OOSDP to provide the needed scientific guidance upon which an effective ocean observing system for climate should be based.

With the publication of this report, GCOS and GOOS have been presented with the scientific guidance that was sought. The comprehensive report of the OOSDP, as well as the related background publications by the Panel, provide a sound rational basis for identifying observational requirements and formulating strategies to develop an oceanographic observation system for climate. In addition to recommendations for elements of the system that are implementable now, the report provides an excellent foundation for future work on those elements which must await development of further knowledge before design requirements can be specified. The conclusions and prioritized recommendations of the report will also serve to guide the development of specific proposals for implementation.

Armed with the present document, GCOS and GOOS should now work together to develop a specific strategy for implementing the essential observational components to bring the climate module of GOOS and the ocean component of GCOS to fruition.

The GCOS and GOOS programs are pleased to receive this OOSDP report, and to acknowledge, with much appreciation, the effort and the dedication of the Chairman and the Panel Members.

## FOREWORD FROM OOSDP CHAIRMAN

The Ocean Observing System Development Panel has formulated with enthusiasm and interest this scientific design of an ocean observing system for climate on behalf of the Global Ocean Observing System and the Global Climate Observing System. We believe that the design is scientifically sound and technically feasible. The recommendations in this report are restricted to those elements of the observing system that can be seen with confidence at this time as essential. A phased implementation of the identified priorities will make it affordable.

To accomplish this, an implementation plan is needed. National institutions must now step forward and make commitments. International institutions are needed to coordinate the activities. A successor to the OOSDP is required for scientific oversight of implementation and to advise on changes in the plan based on new research results and new technology. That new panel should report to both the Global Ocean Observing System and the Global Climate Observing System.

Worth D. Nowlin, Jr., Chairman
Ocean Observing System Development Panel

# SCIENTIFIC DESIGN FOR THE COMMON MODULE OF THE GLOBAL OCEAN OBSERVING SYSTEM AND THE GLOBAL CLIMATE OBSERVING SYSTEM:

# AN OCEAN OBSERVING SYSTEM FOR CLIMATE

## TABLE OF CONTENTS

# SCIENTIFIC DESIGN FOR THE COMMON MODULE OF THE GLOBAL OCEAN OBSERVING SYSTEM AND THE GLOBAL CLIMATE OBSERVING SYSTEM:

# AN OCEAN OBSERVING SYSTEM FOR CLIMATE

## EXECUTIVE SUMMARY

This is a summary of the report, "Scientific Design for the Common Module of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS): An Ocean Observing System for Climate". The report was prepared by the Ocean Observing System Development Panel (OOSDP). This Panel was appointed in 1990 jointly by the Joint Scientific Committee (JSC), sponsored by the World Meteorological Organization and the International Council of Scientific Unions, and the Committee for Climatic Changes and the Ocean (CCCO), sponsored by the Intergovernmental Oceanographic Commission and the Scientific Committee on Oceanic Research-International Council of Scientific Unions. Following the dissolution of the CCCO, the Panel has reported to the JSC and the Intergovernmental Oceanographic Commission. This Report is submitted to the Global Ocean Observing System and to the Global Climate Observing System as the initial scientific design for the ocean observing system for climate. The organization of this summary mirrors that of the full report, although the balance between sections is not maintained.

## I. INTRODUCTION

There are many reasons why an ocean observing system for climate should be designed now and implementation begun. These are discussed in Section I of the report. That section also documents uses and societal benefits that can be derived from such an observing system, as well as non-climate related uses of the information derived from such a system.

Development of models for climate change prediction and analysis depends on more complete and more accurate data sets. Although global change research programs are, or will be, collecting data, such research programs are time-limited; they are not designed for the purpose of providing systematic observations beyond their scheduled completion dates. Some of these data sets are needed as part of an operational ocean observing system for climate; for example, although TOGA ended in 1994, much of its observing system must be continued operationally if the proven benefits of ENSO prediction are to be realized.

If, as most scientists believe, global warming is actually taking place due to increased greenhouse gas concentration, a system of monitoring and model development is necessary to detect it and its rate of occurrence given the background of natural climate variability. This will allow society to have sufficient basis and lead time to intelligently plan ameliorative actions to deal with undesirable manifestations of climate change. For example, the question of how sea level will respond is crucial to many nations and the debate will not be settled without an adequate observing system.

The present state of technology makes the implementation of a truly global ocean observing system feasible now, although ongoing and future developments should greatly improve its capability, efficiency, and economy. Technologies for use now include remote sensing by satellites and variety of in situ instruments, many of which are expendable. Rapid development of additional smart autonomous expendables returning data via telemetry, combined with unmanned observing vehicles and integrating technologies, should further reduce our reliance on research vessels in the future.

To assist in the planning and development of the climate module of the GOOS, the Ocean Observing System Development Panel was given the task of formulating a

> "conceptual design of a long-term, systematic observing system to monitor, describe, and understand the physical and biogeochemical processes that determine ocean circulation and the effects of the ocean on seasonal to decadal climate changes and to provide the observations needed for climate predictions."

This report, supplemented by the eight background reports prepared and distributed under the auspices of the Panel, presents that design.

## II. THE OCEAN AND CLIMATE

The Earth's climate system consists of five major components: the global atmosphere, the world ocean, the cryosphere, the land surface, and the biosphere. All subsystems are coupled, with the complete system exhibiting variations from fractions of seconds to millions of years. The ocean shows variations on all of these time scales; the best understood are those of the diurnal and seasonal cycles, where the response of the system is strong. Interannual variations of the atmosphere-ocean system are beginning to be understood and experimental predictions have shown some skill. Variations with decadal time scales are just beginning to be documented.

It is useful at the outset to describe what we mean by "climate". For the purposes of this document the climate is a set of low frequency averages of variables of interest, with their associated variances. All available information suggests that there has been considerable climate variability over recorded history. This variability may be contained primarily in the variances if the averaging period is long, or in the evolution of both the means and the variances if the averaging is done over a decade or two. A major aspect of the ocean observing system for climate will be to enable the first reliable climatologies (means and variances) of the subsurface ocean to be prepared. This "baseline" climatology is essential for future work on climate change related to the ocean.

We have only a partial understanding of the role of the ocean in the coupled climate system of the Earth. In spite of their widely different time scales, mesoscale ocean eddies, the global effects of an El Niño, deep water formation, and greenhouse gas warming are all manifestations of the complex interactions between the atmosphere, land, and ocean. For the most part they can only be poorly modeled and hence poorly predicted. Although our understanding of ocean climate is increasing through research programs such as those of the WCRP, many aspects require systematic long-term global observations for significant improvements.

A brief description of the ocean's role in climate is given in Section II of the report; More detailed information on the space and time variability of ocean properties is given in Section IV.

## III. SYSTEM DESIGN CONSIDERATIONS

### A. System Design Strategy

Certain general considerations guided the OOSDP in formulating the conceptual design of an ocean observing system for climate.

- Our existing understanding of the ocean is almost completely based on information obtained from research programs, usually within restricted areas.

- Continuity of observational elements is critical because the study of long-term phenomena requires continuity of the data series and its quality.
- Development of models and assimilation procedures is essential for interpretation of data, network design, and quality control.
- New technology is a key to efficiency and effectiveness.
- Our degree of understanding of the climate system determines our ability to define the required observations.
- The system must deal with a continuum of oceanic space and time scales.
- Some degree of redundancy among the observing elements is inevitable.
- There is the need to continuously monitor performance of the observing system.
- The system must continue to evaluate research and technical developments needed for improvement.
- Strategic trade-offs must be re-examined on a continuing basis.

The OOSDP recommends a time-phased approach to implementation of the observing system:

1. In the light of current knowledge:

> a) identify the elements that are part of existing operational systems;
> b) identify elements to be added now to constitute the initial observing system—either enhancements to existing operational systems or parts of existing research observing systems ready for conversion to operational status; and
> c) identify and specify the observations not now readily obtainable that are urgently required and should be added as enhancements to the initial system at the earliest feasible time.
>
> The combination of observational elements included as 1a and 1b comprise the initial observing system of the common module of GOOS and GCOS.

2. Identify future research and development likely needed for further development of the system.

## B. Goals and Subgoals of the Ocean Observing System for Climate

To provide a systematic means for prioritizing observational elements and assessing the projected outcomes of the system design, the OOSDP selected a set of goals and subgoals which relate to the various aspects of the ocean and its role in climate. The choice of a particular set of subgoals that will meet the overall goal of the observing system is of course far from unique. However, in selecting subgoals the Panel attempted to address the key issues regarding monitoring, detecting, understanding, and predicting climate variability and change. It should also be emphasized that these choices were made because they are appropriate now.

1. Surface fields and surface fluxes. Almost all the information needed to determine the ocean's circulation and properties is originally communicated through the air-sea interface, so the estimation of ocean surface fields and air-sea fluxes is a fundamental requirement of the ocean observing system. Sea ice is included because measures of its extent, concentration, and thickness are intimately related to the fluxes of heat and water to and from the ocean. The subgoals are:

   a) To provide in situ measurements of SST that, when combined with satellite measurements, are adequate for defining SST field variability on monthly, seasonal, interannual, and longer time scales. Where it can be determined with sufficient accuracy, sea surface salinity and its variability should be measured.

b) To assist in providing data at the sea surface and in the marine boundary layer needed to estimate global distributions of the surface flux of momentum (wind stress) on monthly, seasonal, interannual, and decadal time scales.

c) To assist in providing data at the sea surface and in the marine boundary layer needed to estimate global distributions of the surface fluxes of heat and fresh water on monthly, seasonal, interannual, and decadal time scales. Additional constraints on these estimates will be provided by estimates from upper ocean budgets.

d) To provide the physical, chemical, and biological data required to describe the global distribution of sources and sinks for atmospheric carbon dioxide and the carbon exchanges within the interior of the ocean. Initially, monthly climatologies of the exchanges are required to resolve longer term changes in the presence of strong variability on interannual and shorter time scales.

e) To provide data to describe the extent, concentration, volume, and motion of sea ice on monthly and longer time scales.

2. The upper ocean. The upper ocean is a buffer to the exchange of heat and other properties between the atmosphere and the interior of the ocean and thus provides the first level of "memory" for the ocean-atmosphere system. The upper ocean is characterized by prominent seasonal to interannual signals suggesting that observation of the upper ocean will be important for prediction and regular monitoring of climate variability over these time scales. The subgoals are:

a) To provide global data for monitoring, understanding, and analyzing monthly to interannual upper ocean temperature and salinity variations.

b) To provide upper ocean data in the tropical Pacific for the initialization and verification of models for ENSO prediction.

c) To provide upper ocean data outside the tropical Pacific for the understanding and description of ocean variability and for the initialization and development of present and future models aimed at climate prediction on seasonal to interannual time scales.

3. The interior ocean. The interior ocean is characterized by its capacity to sequester heat, fresh water, and chemicals from the surface layers and delay exchange for long periods (from decades to perhaps 1000s of years). Deep ocean observations are essential for monitoring and detection of low frequency variations and changes that may be related to anthropogenic forcing of climate. The focus here is more on monitoring, understanding, and validation of model simulations than on prediction. The subgoals are:

a) To provide data to determine the changes in oceanic inventories of heat, fresh water, and carbon on large space and long time scales.

b) To describe changes in the large-scale ocean circulation and its transport of heat, fresh water, and carbon on long time scales through the collection of data and their assimilation in models.

c) To provide measurements of the long-term change in sea level due to climate change; in particular that arising from greenhouse gas warming.

4. The observing system must also focus on providing the infrastructure and techniques which will ensure that information obtained is utilized in an efficient way. The consequent subgoals are:

   a) To provide improved global climatologies (means and variances) of key ocean variables such as temperature, salinity, velocity, and carbon, especially for the purpose of validating probabilistic climate modeling and simulations at decadal and longer time scales.

   b) To provide the data management and communication facilities necessary for routine monitoring, analysis, and prediction of the ocean from monthly to long time scales.

   c) To develop the facilities for processing assembled data sets and providing timely analyses, model interpretations, and model forecasts.

The effectiveness of the observing system in meeting these subgoals will have direct consequences for the specification of an observing system needed to meet the previous subgoals. A more effective methodology for interpolating, extrapolating, and drawing inferences from a measurement system will usually imply a reduced reliance on any one particular observation. Ultimately this synthesis will be performed by ocean general circulation model data assimilation systems which will combine all information from the surface, upper ocean, and deep ocean to produce a multi-variate description of the global ocean circulation. This system does not yet exist, so we now rely on a variety of simpler tools.

## C. Characteristics of Observing System Measurements

The general approach to the ocean climate observing system design developed in this document demands that the measurements meet certain criteria, in effect a definition of what is meant by operational for this observing system. Operational elements should satisfy the following conditions:

- **Long Term**
  Measurements, once begun, should continue into the foreseeable future. Continuity in the observed quantity is sought, rather than in the method; and it is anticipated that more effective methods will become available with time.

- **Systematic**
  Measurements should be made in a rational fashion, with spatial and temporal sampling tuned to address the issues of climate variability and change. Further, measurements should be made with the precision, accuracy, and care in calibration required to provide continuity in the quality of data in space and time even though different methodology may be used.

- **Relevant to the Global Climate System**
  Measurements should be made either to document the role of the ocean in the climate system or to provide data needed to initialize and validate models that describe and predict seasonal to decadal climate change.

- **Subject to Continuing Examination**
  Trade-offs must be subjected to scientific evaluation on a continuing basis to take advantage of new knowledge and technology.

Because of the global scope and intended longevity of the observing system it is realized that there are further practical constraints on the measurements. They should be :

- **Cost Effective**
  Repeated observations are required at many locations. To maximize the return possible using the available resources (financial and manpower), efforts should be made to use observational methods in the observing system that are economical and efficient.

- **Timely**
  Timely delivery of resulting data is required. In some cases this means in real time, while in others substantial quality control will require lapsed time between measurement and data delivery. In all cases data must be delivered to deadlines.

- **Routine**
  The observation tasks should be carried out by dedicated staff, responsible for acquisition and quality control of data and the dissemination of products. Thus for some variables, the collection of observations and related work may be integrated into agencies capable of making a long-term commitment; for other variables, the desired quality of routine observations may be best achieved by providing long-term support to research organizations capable of ensuring the quality and continuity of the measurements. This may vary from nation to nation.

### D. Models and Observing System Design

The role of models and observing system design are discussed in Section III. Models can be used to carry recent information forward to the current period (a forecast initiated from old data), to extrapolate and draw inferences from observations remote from the analysis site (and perhaps from a variety of fields), to combine in a systematic and consistent way disparate information obtained from an operational network. This methodology is commonly referred to as data assimilation or data inversion.

There are few model data assimilation systems operating in oceanography and those that do exist have relatively short histories. For the design of an ocean observing system, data assimilation will enable the optimal extraction of information from the observational data base and, in particular, past information to be extrapolated to the target period. The immediate benefits are less reliance on data from the present period and location (and thus less stringent design criteria) and improved analyses/initial conditions on which to base predictions.

Models are tools for interpolation, extrapolation, and interpretation of observing system information. For many existing ocean model simulations the primary source of information is in the surface boundary conditions, although for ENSO predictions, subsurface information and previous analyses can provide improved initial conditions. In other cases, the ocean model may be statistical and used for the interpolation of unevenly distributed samples to a regular space-time grid.

## IV. SCALES OF OCEAN VARIABILITY

Section IV of the report reviews knowledge of the space/time variability of certain climate variables or quantifiable aspects of the ocean climate system that must be measured or estimated by an ocean observing system for climate. Such climate variables include, for example, sea surface and subsurface temperature and sea surface elevation. Taken together measurements of these fields are fundamental to the determination of:

Oceanic storage (heat, fresh water, carbon, and mechanical energy)
Oceanic transports (heat, fresh water, and carbon)
Air-sea fluxes (momentum, heat, fresh water, carbon, and perhaps dimethyl sulfide)
Circulation measures
    Estimates of water mass renewal rates

Estimates of mass transports
Estimates of velocities

The role of each climate variable needed to determine the quantities listed above is discussed and/or is related directly to meeting the subgoals of III.B.

Knowledge of the space and time scales of variability is essential for the design of an effective observing system. Although the space/time spectra of climatically relevant oceanic variability are in general poorly known at present, our ability to define resolution and accuracy requirements for an observing system will improve as we gain fuller understanding of the scales of variability and physical processes that determine them. Thus, the observing system itself will provide much of the data base necessary to improve our knowledge of this spectrum of variability, so that the future design of climate observing systems can be more firmly based on quantitative statistical and dynamical information.

Section IV cannot be greatly condensed because it is already a summary. For that reason, and because the information in Section IV is background to the system design and does not include design recommendations per se, the interested reader is referred directly to that section.

## V. ELEMENTS OF THE OCEAN OBSERVING SYSTEM FOR CLIMATE

By element is meant an instrument, platform, transmission system, or the processing required to observe a climate variable or quantifiable aspect of the climate system. In Section V of the report the OOSDP gives its recommended elements of the ocean observing system for climate.

The section begins with considerations of measurement platforms now available for potential use in the system. Then, specific recommendations are presented for the observational elements needed to capture the scales of variability identified in the Section IV, to the extent that this is possible, for the following climate variables:

- sea surface temperature and salinity;
- surface wind;
- air-sea heat and water fluxes;
- heat and freshwater transports and budgets;
- upper ocean temperature, salinity and velocity;
- sea level;
- sea ice;
- carbon;
- and measures of full-ocean circulation and properties.

Recommendations are also included for models and for research and development likely to assist in further development of the observing system.

## VI. INFORMATION MANAGEMENT

The recommended ocean observing system for climate will result in vast numbers of measurements and will generate a correspondingly large suite of processed samples, analyses, and products. It must incorporate a sound information management strategy.

Here "information" is defined to include raw and processed data, associated data on measurement methods (metadata), analyzed fields, model output, information on analysis and model methods, and products specifically designed for the user community of the observing system. The "management" includes communications from instruments to responsible centers, quality control, documentation of observing system methods, global communication and exchange of data, data sharing policies, data assembly procedures, regular generation and dissemination of products, and the archiving of information at all stages. "Information Management" conveys the message that the system must manage all information and not just that directly associated with the measured variables.

There exists a background of experience, principles, and international agreements, many developed in support of scientific research, that can be used in developing the information management plan. The following guiding principles are suggested:

- The information management system will be built as possible and appropriate on existing national and international systems;
- The information management system should be "operational" in the sense defined in Section II.C;
- The information management system should be consistent with the objectives, needs, and priorities of the scientific design;
- Data should be transmitted from instrument platforms to appropriate data centers and made available for further processing as soon after measurement as is feasible and practical; timely information transmission and exchange is fundamental;
- Quality assurance of data and products should receive high priority to maximize the benefit drawn from the often difficult and expensive ocean measurements;
- The information management system should be user-oriented to ensure that the needs of users, the ultimate sponsors of the observing system, are served well;
- Full and open sharing of data and information among the participants and users of the observing system is essential to its successful implementation and operation; the proprietary nature of some data collected for scientific research must be recognized and safeguarded, but all such data must be made available to the observing system as soon as possible, reflecting the benefits to the wider community;
- Observing system participants should contribute data voluntarily and with minimal delay to data archival centers which in turn should be able to provide information to users effectively free of charge;
- The observing system will be most effective if practical international standards are developed for all phases of information management;
- Information management will be most effective if it is part of the overall monitoring and evaluation process of the system; thereby enabling new or improved methods and technology to be implemented for the benefit of its overall function. This implies a flexible and evolving management system.

The general goal for the information management system (subgoal 4b) is: "To provide the data management and communication facilities that are necessary for routine monitoring, analysis, and prediction of the ocean state from monthly to long time scales". The aim is to make the flow of information "operational" in the sense defined by the characteristics of the observing system measurements (Section III.C). These objectives are expressed in the goals which must be met by the observing system.

Goal IMS1: To provide for effective data acquisition and communications, including: (i) telemetry between instrument sites and responsible data collection centers; (ii) timely communication of data, analyses and products; and (iii) international standards and protocols for acquisition, processing, and distribution.

Goal IMS2: To facilitate assembly, quality control, compositing, and synthesis of data sets, including: (i) assembly of data sets for the observing system variables from the various data collection points; (ii) provision of effective quality control to the data; (iii) composited and compressed data sets from the various types of measurements for easier utilization and processing, and (iv) performing data rescue as appropriate.

Goal IMS3: To promote the establishment of a distributed system of application centers for the creation of value-added products as required by users.

Goal IMS4: To establish a robust and accessible system for gathering, storing, distributing, and preserving information, including: (i) the implementation of a data base and permanent archive for observing system data, analyses, and products; (ii) maintaining a data base with information on measurement and processing methods and on calibration and validation; and (iii) the creation of a Data Information Unit for the provision of details on the information management system itself.

Goal IMS5: To provide effective management and a workable information exchange policy, including (i) management of the information management system and its interactions with other climate, weather, and ocean systems; and (ii) implementation of an international agreement on the free exchange of information.

A strategy for fulfilling these goals is developed in Section VI of the report. First, existing operational systems are discussed (linkages to the recommended observing system are amplified in Annex II), as are data and information management plans of various research programs that provide the basis of the scientific design. Then, the various levels of data are defined and discussed. Finally, the recommended information management system is be described as distinct, but connected elements which address the goals.

## VII. SYSTEM ORGANIZATION AND EVOLUTION

The process of designing an ocean observing system for climate is evolutionary because our knowledge of oceanic variability and the global climate system is imperfect, the technologies available to us have limited capabilities, and the resources for implementation are finite. An observing system design must take advantage of advances in science and technology.

### A. Enabling Research

By enabling research we mean research that leads to a better scientific understanding of observing system design criteria, and to a better application of the data provided by the observing system. Enabling research may be undertaken explicitly to refine the observing system design, examples of which include correlation scale analyses, observing system simulation experiments, and development of improved data assimilation and initialization schemes for climate models. Enabling research also may be undertaken for the primary purpose of describing or understanding a phenomenon, process, or collection of processes at work in the ocean (i.e., basic research). Though such work may have little direct relationship to observing system design, its consequences may have profound impacts on sampling strategies. Research may also be directed toward the applications of the data and lead to improved data products and better applications.

TOGA offers a good example of how research has influenced the design of an observing system, i.e., for ENSO prediction. The scientific knowledge and understanding regarding many subgoals of the observing system are not as advanced as for the ENSO prediction problem. JGOFS is an ongoing international research program attempting to improve our understanding of the role of the ocean in the carbon cycle and define needed measurements; WOCE is increasing our knowledge of ocean circulation which now limits our ability to formulate and validate numerical simulations of global ocean circulation. Other research programs of the WCRP and the IGBP also will add to the knowledge base needed to further develop the observing system. It is certain that the data derived through the observing system will stimulate research and provide understanding of the climate system in ways not now apparent.

## B. Enabling Technology

The ocean observing system for climate must begin using existing technologies. However, improvements to such technologies, including logistics and communication systems, would result in cost savings and improved performance. Moreover, a number of developing technologies are almost ready for long-term, systematic use, while others are only now emerging but may be useful in the not so distant future. Finally, potential technologies are desired that are not now on the drawing boards.

Existing technologies. One example of how technological refinement has benefited climate studies is the development of the ATLAS wind and thermistor chain mooring (Hayes et al., 1991) which forms the basis of the TOGA-TAO array. Another example is the Autonomous Lagrangian Current Explorer (ALACE), a neutrally buoyant float which periodically rises to the surface from a parking depth as great as 2000 m to transmit data and be positioned by System Argos, resulting in a time series of velocity at the parking depth and vertical profiles of temperature and (experimentally) salinity.

Developing technologies. Examples discussed in the report include:
- The Fast Hydrographic Profiler, an untethered, full-depth CTD profiler (Peterson and Chereskin, 1994);
- A CTD system that can be deployed and retrieved while a vessel is underway, analogous to the old mechanical bathythermograph systems (Dessureault and Clarke, 1994);
- Alternatives for real-time positioning of, and two-way communication with platforms deployed in the ocean;
- Acoustic thermometry to make rapidly repeated measurements of spatially-averaged quantities, such as heat content, over long distances;
- "Slocums", envisioned by Stommel (1989), autonomous profilers of ocean properties, extracting power for buoyancy changes from the temperature gradient in the thermocline;
- The Autosub, an unmanned autonomous vehicle under development by the Natural Environmental Research Council in the U.K. for the collection of subsurface hydrographic data by regularly profiling while traveling along preset ocean transects;
- Electromagnetic devices to provide information about oceanic currents, transports, or averaged temperatures; and
- Estimation of sea ice thickness via measurement of acoustic emissions resulting from ice fracturing.

Potential technologies. Examples discussed in the report include:
- Acoustic data telemetry from subsurface moorings;
- Stable $pCO_2$ and nutrient sensors for use on moorings and autonomous drifters; and
- Satellite remote sensing techniques for SSS.

Summary of technologies. A tabular summary of existing, developing, and potential technologies related to the ocean observing system for climate is included in Section VII. It is based both on published technology development and on responses to a questionnaire soliciting opinions and suggestions regarding "enabling technologies" for the observing system (Annex III). For existing technologies, attempts were made to identify cost attributes, whether improvements are sought, and extent of coverage.

The development process. We envision two major pathways for technology development related to the observing system: (1) development within research programs; and (2) specialized development funded within the observing system. At all stages of these paths, strong scientific oversight must be maintained to ensure that the limited resources available to the observing system are effectively allocated. The observing system management should have the responsibility for supporting the development process and exploiting the potential of new tools to further the aims of the ocean observing system for climate.

## C. Tradeoffs Between Alternative Sampling Strategies

In designing the observing system, it is essential that we realize there are strategic tradeoffs between competing modes of observing many of the ocean components. These alternative sampling strategies must be delineated and examined in the planning phase. And, the observing system must be structured so that it will re-examine these tradeoffs on a continuing basis to take advantage of new knowledge and technology. Examples of tradeoffs between distinct observing modes discussed briefly in the report are alternative approaches to observations of meridional ocean heat flux and to wind stress monitoring.

## D. GOOS Management

The requirements for the ocean observing system for climate are set by the GOOS and GCOS advisory bodies based on the best scientific and technical advice available. Those same bodies, in cooperation with the JSC of WCRP and the Scientific Committee of IGBP, are responsible for defining and evaluating the impact of research developments on potential system improvements. The measurements required to meet the goals and subgoals of the observing system are achieved through an integrated measurement program. The system is completed by assembly, processing, and quality control of the raw data and by analysis and model data assimilation.

The Global Ocean Observing System includes ongoing strategic planning to set requirements for the system, monitor performance, define and evaluate research and technical developments for potential improvements, and examine strategic sampling tradeoffs. These functions may not be carried out by a single body or institution, but all must be supported and carried out coherently as part of the system.

The board of directors for GOOS is the Intergovernmental Committee for GOOS (I-GOOS). I-GOOS interacts with Nations, the IOC, the WMO Executive, and other groups. The Joint Scientific and Technical Committee for GOOS (J-GOOS) is its senior scientific/technical body, reporting formally through I-GOOS. J-GOOS provides I-GOOS with recommendations to ensure efficiency and re-direction of the system. A GOOS Support Office provides a permanent staff for I-GOOS and J-GOOS. Reporting to I-GOOS are the various commissions which implement and operate GOOS. Close connections must be maintained with GCOS and WMO.

J-GOOS provides scientific and technical design oversight and advice. It should possess a measure of scientific independence, and should be linked to the JSC of the WCRP and the JSTC of GCOS to establish clearly the links of GOOS to climate research and broader climate monitoring. It should have scientific expert panels, like the present OOSDP, to continue planning and refinement of the GOOS modules, specifically the Ocean Observation Panel for Climate (planned successor to OOSDP) and the panel responsible for the Health of the Ocean module. It is suggested that the successor to OOSDP be appointed jointly by J-GOOS, GCOS JSTC and WCRP JSC.

The Panel proposes a separate unit, called the "Evaluation Unit", to assist with continuing monitoring of performance, evaluation of technical developments, and examination of sampling tradeoffs. This unit must have the resources to undertake rapid evaluation of the day-to-day system operation as directed by the GOOS management, with emphasis on ensuring that processed data are flowing at the requisite rates, sampling density, and quality. Although permanent, this unit might be distributed among different centers, with much of the work done by appropriate specialists under contract.

# VIII. SYSTEM INTEGRATION; SYNTHESIS

Section III.B presents a set of goals and subgoals appropriate for the design of the ocean observing system for climate. Then, Sections IV and V provide information regarding the various components of the ocean climate system, their scales of variability, and suggested suites of observations required for proper temporal and spatial sampling. There the focus was on description of air-sea exchanges, interocean fluxes, and storage of heat, freshwater, carbon, etc. In Section VIII focus is returned to the goals and subgoals of the observing system design and the best mix of techniques for meeting these goals. In carrying out this prioritization, the OOSDP did not include the research and development activities recommended in Section V as needed to support and advance the observing system.

## A. Observing System Elements versus Subgoals

First, the Panel considered the totality of subgoals to which each recommended observational element would contribute. Table VIII.A.1-1 in the report indicates all subgoals to which each of the recommended elements/observations contributes. Consideration of the number of subgoals to which an element contributes may provide one measure of overall priority for that element within the observing system; while not of highest priority to any specific goal, some observations may contribute in some measure to attaining a large number of subgoals. On the other hand, a certain element may be essential to meeting a specific subgoal yet not be useful for attaining other subgoals.

Then, for each subgoal, the OOSDP considered each observational element needed to meet that subgoal with regard to its characteristics and its importance in meeting the subgoal. The report reviews the current state of scientific knowledge in regard to the various components of the climate system and provides scientific justification for the application of various measurement and analysis techniques. The issue then is the relative impact of these contributions to the scientific subgoals. This subjective evaluation is referred to here as the scientific *impact.*

The issue of relevance is key to the assignment of *impact*. The long-term characteristic is not at issue because it is assumed that observing system measurements will be continued indefinitely—or until replaced by a better measure/technique. The other main considerations are that the measurements (and analysis and management systems) should be routine, systematic, cost effective, timely, and subject to continuing examination. The Panel has adopted a subjective assessment which we term *feasibility* as a relative appraisal of the extent to which an element satisfies these characteristics. Implicit in this judgment is some unspecified weighting between the routine, systematic, timely, and cost-effectiveness characteristics. The latter factor is not treated in any precise way.

For each subgoal, the Panel has prepared a schematic diagram showing the ranking of each recommended observational element for that subgoal in terms of its *feasibility* and *impact* in attaining that subgoal. Note that these schematics are not the total picture and sometimes over simplify the realities of taking observations or delivering products. Nevertheless the Panel felt it is important to make these deliberations as explicit as possible.

For both *impact* and *feasibility* a low, medium, or high weighting is assigned to each element taking into account the foregoing considerations. Note the implication that the measure is relative (to other elements for that subgoal) and not absolute. The observational elements are shown as measurements or estimates needed; platforms/tools are indicated if more than one option are available.

On the feasibility-impact diagrams (Figures VIII.A.2-1 to 11 in Section VIII) the observing system elements are classified as belonging to one of the same three categories stated in Section III and used in Section V in formulating the recommendations for the required system elements, that is, (a) as part of existing operational systems, (b) to be added to complete the initial observing system, or (c) enhancements to the initial observing system to be added later. Categories (a) and (b) together constitute the recommended initial observing system. In addition, each element is referenced to the numbered recommendations of Section V. The feasibility-impact diagrams do not include recommended research and development activities.

With each feasibility-impact diagram, text is provided summarizing the observing system elements needed to meet the subgoal and the deficiencies of the observing system given present knowledge and technology. These are provided here with the statement of the subgoal.

**Subgoal 1a:** To provide in situ measurements of SST that, when combined with satellite measurements, are adequate for defining SST field variability on monthly, seasonal, interannual, and longer time scales. Where it can be determined with sufficient accuracy, sea surface salinity and its variability should be measured. (Refer to Figure VIII.A.2-1.)

Notes: SST is a variable for which a product now exists and this has guided the OOSDP recommendations.

The minimum set of requirements are:

- existing operational measurements now contributing to SST products (AVHRR with in situ SST from VOS and buoys);
- SST from ATSR;
- SST from a subset of VOS with improved sensors;
- SST from drifters in data sparse regions; and
- conductivity and SST from selected moorings.

At present, SST is obtained using AVHRR measurements from space combined with in situ SST from standard VOS and from drifting and moored buoys, including the TAO array. The buoy data, because of their accuracy, have the most impact on the calibration of the AVHRR data. The initial system needs the addition of further observations for calibration. This includes measurements of SST from drifters in data sparse regions, such as the Southern Ocean, and from a subset of VOS fleet equipped with improved (hull contact) temperature sensors. ATSR SST should be used to establish transmission errors in satellite SST data. Limited SSS observations are now available from some buoys, including the TAO array. This coverage should be increased. It should be noted that information from sea ice analyses (subgoal 1e) is used in SST analyses, although that is not shown in the diagram.

The system would be improved by:

- SST observations in special regions and
- SSS observations from VOS and drifters.

In certain regions, satellite SST observations are inadequate because of cloud cover or other problems and increased in situ observations are required to provide sufficient accuracy and resolution. Although global SSS coverage is not feasible at present, the development of the operational use of thermosalinographs on VOS and conductivity sensors on drifters could provide critical data. On the longer term, improvements need to be sought in both in situ measurements and those from space, perhaps including SSS.

Deficiencies. The lack of satellite data relay capability now limits the volume of data that can be retrieved from surface buoys and ships, and thus the number of such platforms that can usefully be deployed. This, together with limitations in our ability to take in account differences between skin temperatures observed by satellite and in situ observations, limit our ability to define the SST field.

The lack of operational thermosalinographs, affordable, proven salinity sensors for buoys, and a remote sensing capability for salinity limits our ability to obtain global SSS observations.

**Subgoal 1b:** To assist in providing data at the sea surface and in the marine boundary layer needed to estimate global distributions of the surface flux of momentum (wind stress) on monthly, seasonal, interannual, and decadal time scales. (Refer to Figure VIII.A.2-2.)

Notes. The only global wind or wind stress products presently available are those derived from NWP analysis. Even if a proven operational scatterometer becomes available, NWP analyses and the observations they assimilate will continue to play a major role in defining the ocean observing system for wind stress.

The minimum set of requirements are:
- existing surface meteorological observations from VOS and buoys and NWP analyses;
- an operational satellite scatterometer;
- SLP from Southern Ocean drifters;
- surface wind from TAO; and
- improved VOS observations.

At present estimates of the large-scale surface wind are primarily obtained from the analyses of NWP models that assimilate a variety of ocean data which have high impact. These include SST analyses, VOS meteorological observations and buoy data. Scatterometer data have the potential for providing the wind stress, and data for assimilation into models; however an operational scatterometer system has yet to be implemented. There is also a requirement for more and improved in situ observations. In particular, drifter SLP is needed in the Southern Ocean for input to NWP models, and direct wind observations from the TAO array are required for ENSO prediction. It also is feasible to improve VOS observations through changes in procedures. Measurements are needed for calibration of satellite observations and these may be obtained from moored arrays (see also subgoal 1c). It should be noted that information from sea ice analyses (subgoal 1e) is used in preparing global air-sea flux estimates, although that is not shown in the diagram.

The system would be improved by:
- improved wind measurements on a subset of VOS.

Depending on the success of an operational scatterometer wind system, consideration should be given to improvement of wind measurements on a subset of VOS using better automated systems. Wind stress might be obtained using the inertial dissipation technique. Satellite wind speed products from radar altimeters or passive microwave radiometers may also be used, but the first is limited by restricted spatial coverage and the second by accuracy.

Deficiencies. Present NWP models produce wind fields that differ from one another, especially in data sparse regions. Reliance in the future on such fields will require efforts to improve both the availability on a global basis of in situ winds and the performance of the models. Use of satellites to fulfill subgoal 1b requires a commitment to operational deployments of such satellites with orbits chosen to provide reasonable global coverage and continued efforts to improve satellite algorithms for determining wind and wind stress.

**Subgoal 1c:** To assist in providing data at the sea surface and in the marine boundary layer needed to estimate global distributions of the surface fluxes of heat and fresh water on monthly, seasonal, interannual, and decadal time scales. Additional constraints on these estimates will be provided by estimates from upper ocean budgets. (Refer to Figure VIII.A.2-3.)

Notes. For the determination of heat and water fluxes the only feasible approach is to use the fields produced by NWP models in conjunction with in situ and satellite observations. Thus, the elements of the ocean observing system for climate for air-sea fluxes (sensible and latent heat, radiation, and precipitation) have been defined as follow.

The minimum set of measurements are:
- existing NWP surface flux analyses and the existing VOS, buoy, and satellite-based observations in their support;
- improved meteorological observations from VOS;
- in situ radiation observation on VOS; and
- regional flux verification arrays.

Given the role of NWP models in the determination of surface fluxes, priority has to be given to critical observations for assimilation into them and for verification and improvement of the algorithms used in their codes. Such data have high impact; they include SST analyses and VOS meteorological observations that include surface radiation and precipitation and are of improved accuracies. Satellite precipitation and radiation estimates would also have high impact if the required accuracy can be obtained. There is a requirement for data to verify model flux determinations. The latter include quality surface observations from VOS and buoy arrays designed for flux verification. The improved VOS observations are possibly more feasible, however the buoy data would be expected to be more accurate and therefore of higher impact. It should be noted that information from sea ice analyses (subgoal 1e) is used in preparing global air-sea flux estimates, although that is not shown in the diagram.

The system would be improved by:
- operational satellite measurements for ocean surface flux determination.

There is a need to define operational satellite measurements for ocean surface flux determination, making remotely-sensed radiation and precipitation fields, calibrated with in situ data, available in a timely manner similar to present SST products. These are expected to place emphasis on determining surface insolation, wind velocity, and precipitation. Consideration should also be given to the long-term determination of direct flux observations, including precipitation, from a variety of platforms. Improved surface flux determination depends on improved satellite observations, the effective assimilation of both in situ and satellite-based observations in NWP models, and the existence of direct flux measurements for flux verification.

Deficiencies. The challenge of obtaining surface heat and freshwater fluxes on a global basis is significant. NWP models are limited by their need for computational efficiency in how sophisticated their parameterizations of clouds can be. This in turn limits their ability to predict radiative fluxes and freshwater flux at the sea surface. Satellites provide radiation at the top of the atmosphere. Satellite surface radiation estimates, like other heat flux related measurements, are limited by the difficulties related to the ability to resolve the vertical structure of the atmosphere. Operational, in situ, open ocean rain measurements of proven accuracy remain an elusive goal; and this limits the efforts to improve satellite sensing of precipitation.

**Subgoal 1d:** To provide the physical, chemical, and biological data required to describe the global distribution of sources and sinks for atmospheric carbon dioxide and the carbon exchanges within the interior of the ocean. Initially, monthly climatologies of the exchanges are required to resolve longer term changes in the presence of strong variability on interannual and shorter time scales. (Refer to Figure VIII.A.2-3.)

Notes: Recent observations of atmospheric $CO_2$ concentration show a decline in the rate of increase for the years 1991 to 1993. Lack of observations prevents us from determining the contribution of ocean processes to this effect. Therefore, one priority for the observing system is to resolve the annual time scale for ocean-atmosphere exchanges of $CO_2$. Although this subgoal focuses on annual time scales and the upper ocean, in the longer term the accumulation of systematic observations of the upper ocean will be compared with changes in the ocean inventory of carbon and its transport by the full depth circulation (subgoals 3a and 3b).

The minimum set of requirements are:
- $pCO_2$ from manned VOS and
- fluorescence from manned VOS.

Initially, the system requires enhancement of the existing research measurements of $pCO_2$ and fluorescence on manned VOS. Where possible the $pCO_2$ measurements should be accompanied by the analysis of the $^{13}C/^{12}C$ ratio of $pCO_2$ in discrete samples. The system requires wind products for calculations of exchange rates in the sampled areas. Global wind and SST products are also needed for extrapolation to the global scale.

The system would be improved by:
- $pCO_2$ from unmanned VOS;
- $pCO_2$ and fluorescence from drifters; and
- ocean color from satellites.

Measurements of ocean color from research satellites will be available shortly and help provide global coverage of chlorophyll, which is a proxy of the role of the biological pump in absorbing $CO_2$. Ground truth has to be provided first by VOS and then by drifters equipped with $pCO_2$, fluorescence, and SST sensors. In addition, drifters will enhance the space and time coverage of VOS. For the annual time scale, this constitutes the minimum system for resolving fluxes on a global scale.

In the future, this basic system would be considerably improved with the addition of nutrient sensors, particularly nitrate, on VOS and drifters. This would allow large improvements in the design on physical-biogeochemical models as well as their validation.

Deficiencies. The basic system cannot meet the goal to describe carbon exchanges with the ocean interior. There are multiple physical and biogeochemical processes that exchange carbon between the surface layer and the interior ocean. At present, the relative importance of these processes in determining the net flux into the interior and the critical time and space scales at which they operate remain poorly understood. Much more information and syntheses from the JGOFS process experiments and time series will be required before a credible observational strategy can be defined. At the same time, the ocean observing system will require process models that can assimilate both remotely sensed (e.g., ocean color) and in situ biogeochemical data to interpolate fluxes over regional and global scales. This is also a principal goal of JGOFS.

**Subgoal 1e:** To provide data to describe the extent, concentration, volume, and motion of sea ice on monthly and longer time scales. (Refer to Figure VIII.A.2-5.)

Notes. As part of the cryosphere, sea ice is a basic component of the climate system. It forms a barrier between the ocean and atmosphere and its seasonal growth, movement, and decay are important in global exchanges of heat and fresh water. In both the Arctic and Antarctic, sea ice influences the creation of deep water masses. On long time scales, it is thought to be a sensitive indicator of climate change. The emphasis is on developing a long-term climatology of sea ice and its variability that can be used to monitor climate change and to test and validate model simulations.

The minimum set of requirements are:
- global sea-ice extent and concentration estimates from passive and active microwave satellite observations and, in specific regions, from SAR and

- ice drift using tracked drifting buoy networks.

Microwave sensors provide the only all-weather method of obtaining global estimates of sea-ice extent and concentration, but serious problems remain in their interpretation. In clear skies, the average albedo can be estimated from visible channel data or AVHRR imagery. Sea-ice regions vary greatly in character and there is difficulty in establishing algorithms to describe sea-ice concentration in the presence of snow cover, melt water, thin ice, ice of different year classes, etc. Measuring ice velocity using drifting buoys is a proven technique, but existing networks in the Arctic and Antarctic are sparse and regional in spatial coverage.

The system would be improved by:
- routine determination of ice drift using SAR and
- upward-looking sonar measurements of ice-thickness from moored arrays.

High spatial resolution fields of ice motion can be obtained from SAR (as on Radarsat) by tracking floes. In order to routinely obtain large-scale synoptic measurements, the development and application of automatic techniques is required. Measurement of ice-thickness from space does not seem to be feasible. Limited upward-looking sonar measurements have been made in the Arctic both from submarines and research moorings, although much of the former data are not now available. Regional buoy arrays, such as planned for the Arctic under the ACSYS program would provide data to monitor long-term change and to improve and validate sea-ice models.

Deficiencies. The recommended system is deficient in meeting various aspects of subgoal 1e. One serious lack is the existence of any technique to determine ice thickness or volume on global scales. Another is the inability to accurately estimate the fractions of thin ice and open water which are important as regions of intense air-sea heat exchange. Improvement may come from the various research programs which are obtaining local or regional in situ data which can be used both to improve the algorithms used to interpret satellite data and to develop improved models of ice growth and transport. A goal for the future would be the assimilation of available data in improved coupled ocean-atmosphere-sea-ice models on an operational basis.

**Subgoal 2a**: To provide global data for monitoring, understanding, and analyzing monthly to interannual upper ocean temperature and salinity variations. (Refer to Figure VIII.A.2-6.)

Notes. This subgoal is principally concerned with the determination of low-frequency temperature and salinity changes on spatial scales greater than that of oceanic variability (e.g., mesoscale eddies). It is not concerned with prediction. The observation network recommended here, in conjunction with surface products and upper ocean data gathered for other purposes, aims to provide relentless data collection which, over time, will result in an accurate determination of the mean state and variance of the temperature and salinity fields and of long-term changes in upper ocean storage.

The minimum set of requirements are:
- an upper ocean temperature sampling program, principally using VOS XBTs in broadcast mode, supported wherever possible by opportunistic sampling on research and Antarctic supply vessels;
- wind stress, SST, air-sea heat flux (from subgoals 1a, 1b, and 1c); and
- SSS and/or air-sea freshwater flux, particularly in regions where salinity is known to be critical.

The foundation of the upper ocean observation program will be provided by a broadcast XBT sampling network using VOS; in essence this recommends maintenance of the present research VOS XBT network sampling according to the broadcast mode strategy. There should be a concerted effort to maintain an XBT program on Antarctic supply vessels as this is one of the few strategies available for collecting data in these regions. At present there are few operable alternatives for obtaining upper ocean temperature other than the use of subsurface autonomous floats (e.g., ALACE) which can obtain temperature, and perhaps salinity, profiles in the global ocean.

For monitoring of low-frequency change it is critical that the surface wind and thermohaline forcing is known. The wind stress is critical for calculating the horizontal flux of heat due to surface Ekman currents. SST (or surface heat flux) is required for the surface thermal boundary condition; present knowledge would suggest SST is the most critical. In some cases, such as in the subpolar gyre of the North Atlantic, it is also critical to monitor upper ocean salinity. In the absence of a viable strategy for sampling upper ocean salinity profiles it is important that every effort is made to determine surface salinity or, if possible, the net surface water flux. Necessary surface fields are provided for by the strategies outlined for subgoals 1a, 1b, and 1c.

The system would be improved by:
- vertical T and S profiles using subsurface floats;
- sea level (altimeter); and
- subsurface salinity (as the opportunity arises).

Altimetry offers the possibility for global coverage that is not feasible by other means. It does not directly give any information on temperature or salinity, or on their variation with depth, but it does provide an estimate of their combined, vertically integrated effect, and so would provide valuable additional information on long-term changes in storage and transport, and on the strength of the major gyres.

It is also important that the observing system endeavor to improve our knowledge of the annual salinity cycle, particularly at high-latitudes. This requires continued technological development of the XCTD, but if, as seems likely, this instrument can be produced with the required reliability and accuracy, and at reasonable cost, a subset of the VOS should be used to improve the sampling of upper ocean salinity.

Deficiencies. The most important deficiency of the basic system recommended here is that it does not guarantee global coverage. The lack of salinity measurements can be tolerated; the lack of temperature measurements is a more serious weakness. There is also a strong dependence on surface fields and fluxes. It is not certain that the estimates of the surface fluxes of heat and moisture will be adequate for the purposes here.

In a sense these deficiencies have been acknowledged in the framing of the subgoal; the focus is on large-scale, low-frequency monitoring and analysis. However, the realities of the available technology mean that even this objective is hard to reach. The strategy relies on long periods of sampling to overcome uncertainty due to the lack of temporal and spatial resolution, but the success of this strategy cannot be assured. Depending upon the results of WOCE, it may be desirable to augment the broadcast mode sampling with selected high-density XBT lines. The benefits of a routine, relentless program of data collection will only be realized in the long-term, but it is an outcome worth pursuing.

**Subgoal 2b:** To provide upper ocean data in the tropical Pacific for the initialization and verification of models for ENSO prediction. (Refer to Figure VIII.A.2-7.)

Notes. This subgoal has been separated from the more general prediction problem (subgoal 2c) because there is proven feasibility of monitoring and predicting seasonal to interannual variability associated with the ENSO phenomenon.

The minimum set of requirements are:

- wind stress (subgoal 1b);
- SST (subgoal 1a); and
- upper ocean temperature (TAO + VOS + ALACE) [not as high priority as wind and SST].

Knowledge of surface wind stress in the tropical Pacific Ocean has been acknowledged as the most important information element for ENSO prediction. It is used directly in stochastic prediction schemes and indirectly to initialize simple and complex models for analysis and prediction of equatorial Pacific Ocean temperature. SST is the most widely used oceanographic parameter in monitoring interannual variability in the Pacific Ocean and is also used in stochastic and deterministic model predictions.

Upper ocean temperature data have become important in ENSO monitoring and analysis activities, probably more useful than SST alone. There is also mounting evidence that upper ocean data will be critical for improving the skill of ENSO model predictions; the results of TOGA are sufficient to conclude that such data are necessary, but for the present we cannot state that they match the priority of wind stress and SST.

The system would be improved by measurements of:

- sea level (a combination of in situ and altimetry);
- surface currents;
- subsurface currents on a subset of TAO; and
- climatology of SSS (for model boundary conditions).

On available evidence it would seem that the best opportunity for improved prediction skill is through better models and improved model data assimilation. Surface and subsurface current data are required for validation of ocean models and for independent monitoring of heat transports by ocean currents. Sea level provides an indirect measure of the tropical ocean response to wind forcing and ocean heat storage. It has a long history of use as a monitoring tool and is useful for model validation. It can be anticipated that altimeter data also will be useful for model initialization. The majority of ocean models include salinity as a prognostic variable; SSS is required as a surface boundary condition though, at this time, there is insufficient evidence to warrant a campaign for real-time determination of SSS.

Deficiencies. While there is significant research still to be done, it would seem that improvements in ENSO prediction will not be limited by the observation network recommended above; it is necessary and adequate. The limitations are provided by the models used for prediction and, in particular, the limitation of coupled ocean-atmosphere GCMs. The recommended observations will be critical for this model improvement. There is insufficient scientific evidence to recommend real-time collection of salinity data (say, from XCTDs) or ocean current data for initializing prediction models. The latter will be the most useful for validation. On existing evidence there is not a strong case for surface heat flux or surface moisture flux as boundary conditions for prediction models, though their use as validating fields for models is important.

**Subgoal 2c**: To provide upper ocean data outside the tropical Pacific for the understanding and description of ocean variability and for the initialization and development of present and future models aimed at climate prediction on seasonal to interannual time scales. (Refer to Figure VIII.A.2-8.)

Notes. Here the primary objective is prediction from time scales of weeks out to interannual, ideally for the global domain and spatial scales ranging from regional out to gyre scale. In essence it is the generalization of subgoal 2b to the global domain and to variability over a broader range of time scales. At present such prediction is only feasible on regional scales, and then only if there is a superior data coverage to allow proper initialization. The recommendations recognize the worth of supporting regional "pilot" activities as well as taking a more long-term view for the global problem.

The minimum set of requirements are measurements of:
- global sea level by altimetry;
- wind stress; and
- SST.

It is not clear whether these elements constitute the absolute minimum for a prediction program; insufficient research has been done at present. However, on the basis of available research, it would seem that a combination of altimeter data (as a proxy for thermocline deviations), SST (for surface structure and fine detail), wind stress, and advanced model data assimilation techniques offer the best strategy. The reality is that such a system may not be realizable in the short term. Certainly, altimetry seems to offer the only practical alternative for understanding mesoscale variability.

It may however prove necessary, in addition to the minimum set of requirements given above, to obtain large-scale thermal data in the upper ocean from an expanded program of VOS XBT observations and/or the use of profiles from autonomous floats. Other types of data may be required on regional scales.

Alternative observational elements (in approximate order of priority) are:
- subsurface temperature from VOS and floats and
- currents from drifters and ADCPs.

For some regions it is possible to gather enough in situ upper ocean temperature data to monitor upper ocean variability including boundary currents. When merged with satellite SST data it is possible to reconstruct the fine-scale subsurface structure ("feature" analysis). Drifters and ADCP data from VOS and research vessels provide additional information. For this subgoal such data sets and analyses (and perhaps predictions) can be viewed as regional "pilot" observing systems from which a more general, global system might be evolved.

Deficiencies. The outcomes from this system are limited both by available data and by lack of scientific knowledge. The implementation of a basic observing system will rely on technological developments and on ongoing research programs such as CLIVAR. In the meantime, the observing system must foster regional activities even if they may not be entirely within the present definition of ocean climate.

**Subgoal 3a**: To provide data to determine the changes in oceanic storage and inventories of heat, fresh water, and carbon on large space and long time scales. (Refer to Figure VIII.A.2-9.)

Notes. Changes in the heat, fresh water, and carbon content of the full depth ocean on large space and long time scales are sensitive indicators of climate change. They are indicative of changes in water mass formation and represent the only possibility of observing the small changes in surface fluxes that are predicted to occur with increasing greenhouse gasses. This subgoal is complimentary to subgoal 2a addressing the upper ocean and depends on it. Both address the need for a long-term relentless program of data collection which over time will determine the slowly evolving oceanic heat, fresh water, and carbon storage.

The minimum set of requirements are:
- a program of transocean sections, measuring T, S, carbon, carbon-14, and selected tracers;
- profiles of T and S using autonomous floats;
- repeat hydrographic sections in critical regions for water mass formation; and
- upper ocean heat and fresh water content (from subgoal 2a).

Hydrographic sections are the proven technique for measuring oceanic heat, fresh water, and carbon content and form the basis for measurements of the greatest accuracy. Simultaneous measurements of carbon-14 and selected tracers (e.g., chlorofluorocarbons) allow some determination of the age of particular water masses and of their origin. As for subgoal 3b, the interval between repeats of transoceanic sections needs to be determined by experience—such is being obtained from the repeat occupation of sections in the North Atlantic including 24°N in 1957, 1981, and 1993, and by time series of high-density lines of XBT and XCTD observations. Given the uncertainty of the interval between repeats and because of the recent global coverage being provided by WOCE, transocean sections, although essential, have been classified as enhancements to the initial system in this report. Measurement of changes in integrated heat, fresh water, and carbon storage requires distributed observations. Repeat hydrographic stations, required for the determination of heat and freshwater fluxes, contribute to this objective as will high quality data from research programs. Selected tracers should be considered for measurement if they can be used as surrogates to establish carbon inventories. For heat and fresh water content, profiles of T and S from a well distributed array of autonomous floats would provide basic information, especially in remote areas. Repeat sections are also required to monitor water mass formation in certain regions. An example is provided by the yearly spring time occupation of a section across the Labrador Sea which provides information on the extent and characteristics of the yearly formation of Labrador Sea Water by deep convection.

The system would be improved by:

- time series stations of T, S, and carbon and
- measurements of sea ice volume.

Although a time series station only gives information on the local storage of heat, fresh water, or carbon, where they exist, for example Station S off Bermuda, they appear to be representative of a larger area. In addition, they provide information on the variability on seasonal and longer time scales that is vital for the interpretation of the necessarily low temporal resolution of global measurements. Some such stations already exist and should be continued as part of the initial observing system (as indicated in the figure); other selected stations would enhance the observing system. Acoustic thermography offers promise as a tool to observe some low frequency changes in the oceanic thermal structure integrated along the acoustic pathways. However, evaluation of this technique awaits the results of experiments such as ATOC. Global measurements of sea ice volume would further improve our knowledge of freshwater transports and budgets, but seem remote at this time.

Deficiencies. It is clearly a formidable task to measure even the long time, large scale storage of heat, fresh water, and carbon in the face of the known and different time and space scales that exist throughout the water column. Nevertheless, the recommended measurements when interpreted with the aid of information regarding changes in oceanic transports obtained under subgoal 3b are sure to advance our knowledge of this important aspect of climate change. Initially, implementation should be focused on areas where the signal is expected to be large and logistics are feasible, but ultimately global measurements are required.

**Subgoal 3b:** To provide data to describe changes in the large-scale ocean circulation and its transport of heat, fresh water, and carbon on long time scales. (Refer to Figure VIII.A.2-10.)

Notes. This subgoal is concerned with changes in the full depth oceanic circulation on interannual and longer time scales. Given our present knowledge of the deep ocean, it is not concerned with collecting data to initialize deterministic predictions. The objective is rather to describe low frequency changes in the circulation and its related transports of heat, fresh water, and carbon that are known to occur naturally and are predicted in the future as the result of increasing greenhouse gases. Of obvious importance for an optimum design of an ocean observing system to meet this subgoal is the completion of WOCE and JGOFS and the results of future research programs of the

WCRP and IGBP. Nevertheless, given present knowledge it is possible to specify a set of systematic observations for this subgoal which need to be maintained for the foreseeable future and which will not in general be supported as part of research programs.

The minimum set of requirements are:
- sea surface elevation from a precision altimeter;
- wind stress and SST (from subgoals 1a and 1b);
- a program of transocean sections, measuring T, S, carbon, carbon-14, and selected tracers (e.g. chlorofluorocarbons);
- subsurface velocity and profiles of T and S using autonomous floats;
- sea ice extent and drift (from subgoal 1e); and
- river discharge.

Sea surface elevation obtained from altimetry provides the only presently available global measure of the response of the ocean to changes in surface forcing, especially that related to changes in wind stress which must also be determined. On interannual and longer time scales, there is known to be natural variability in the interior ocean large-scale mass field and the vertical structure of geostrophic currents. Similar changes are predicted to arise from increasing greenhouse gases. Two techniques can be used to quantify the resulting change in the oceanic circulation and its transport of heat, fresh water, and carbon. First, repeat hydrographic sections taken across ocean basins provide a measure of changes in the baroclinic flow and of the transport of heat, fresh water, and carbon across the section. The time interval between repeat occupations of sections needs to be determined by experience and the result of research programs. Analysis of single sections can use the methods introduced by Hall and Bryden (1982) and multiple sections can take advantage of a higher order inverse or model-based techniques. Second, an array of autonomous floats at a deep reference surface provide a direct measurement of the generally weak, but fundamentally important, deep flow as is being shown in WOCE. Such floats, when equipped to measure T and S during regular trips to and from the surface, can provide an evolving three-dimensional description of the T, S, mass, and available potential energy fields suitable for assimilation and analysis by ocean GCMs resulting in a description of circulation variability. To measure the flux of fresh water, observation of river runoff and sea ice extent and drift are required.

The CFCs are valuable tracers to compute and follow the distribution of carbon inventories in the ocean for three main reasons: they are inert compounds; their atmospheric input function is well known (which is not the case for tritium); and there is no pre-anthropogenic background. Until now the use of CFCs to calibrate OGCMs or compute inventories has been restricted by a lack of global, near synoptic data coverage in the past. It is certainly unfortunate that the data collected by numerous investigators over the past 10-15 years has still not been compiled in a single data base. This situation must be improved in the near future. An active international cooperation on measurement and calibration exists today under the WOCE program.

The system would be improved by:
- measurement of inter-basin exchanges;
- boundary current monitoring;
- sea surface fluxes of heat, freshwater, and carbon (from subgoals 1c and 1d);
- SSS and surface $pCO_2$ (from subgoal 1a);
- sea ice thickness; and
- a marine geoid satellite mission.

Measurements of the transport of water, heat, and salt between ocean basins provide strong constraints on the global circulation and its variability. Unfortunately, such measurements now are feasible only where the flow is constricted in a passage of limited width. Two important inter-basin exchanges meeting this criteria are between the Pacific and Arctic Oceans through Bering Strait and between the Indian and Pacific Oceans through the Indonesian passages. Measurements of boundary currents also provide information on changes in the circulation but suffer from difficulties in determining whether changes in the boundary current are compensated by flow elsewhere. However, the existing cable measurement of the Gulf Stream in Florida Strait is an example of a record that should be maintained. Measurement of absolute ocean currents using altimetry is limited by lack of knowledge of the marine geoid. This would be improved by a special dedicated satellite gravity mission. Knowledge of spatial and temporal changes in the surface fluxes of heat, fresh water, and carbon can aid in the interpretation of variability observed in the ocean circulation and the transport of these quantities. However, at present the accuracy to which these fluxes can be determined is such that on long time scales, net fluxes seem to be better determined by interior ocean measurements (see also subgoal 3a). The inability to obtain accurate surface fluxes increases the importance of measuring SST globally and SSS and $pCO_2$ where they can be obtained from VOS.

Deficiencies. The recommended system is limited in its ability to resolve strong current systems (and their transports of heat, fresh water, and carbon) that are of limited spatial extent but are nevertheless important elements of the oceanic circulation. An example is the lack of a viable technique to measure changes in these transports by the Antarctic Circumpolar Current through Drake Passage. There is also the inherent difficulty in interpreting long period changes in the circulation and its transports using infrequent measurements in the presence of mesoscale variability. The logistical difficulty of putting in place the recommended measurements globally, especially in the Southern Ocean, is also evident. Nevertheless, the emerging experience of WOCE and development of more realistic ocean models capable of aiding in the interpretation of ocean data indicate that the recommended system is a significant step towards meeting the subgoal.

Improved bathymetry is required in many regions of the global ocean because of the strong effect bottom topographic features such as ridges and passages have on ocean circulation. Without improved bathymetry interpretation of changes in sea surface elevation and the interior mass field in terms of changes in the circulation will remain problematical in some regions.

**Subgoal 3c**: To provide measurements of the long-term change in sea level due to climate change; in particular that arising from greenhouse warming. (Refer to Figure VIII.A.2-11.)

Notes. This subgoal is directed at putting in place the capability to observe the long-term change in sea level expected as a result of increasing greenhouse gases. The likely increase due to oceanic thermal expansion alone has been estimated as 2-4 cm/decade (IPCC, 1992). Additional change could arise from ablation of glaciers and ice sheets. The "observed" change in sea level over the past 50 years has been estimated by Barnett (1983b, 1984) and others from the analysis of tide gauges to be of order 1-2 cm/decade. However, these estimates are uncertain both because of the small number and distribution of tide gauges with sufficient record length and because of the difficulty of accurately accounting for isostatic changes at the location of the tide gauges.

The minimum requirement is for:

- A number of high quality tide gauges (of order 50) geocentrically located in an earth reference system and
- A precision satellite altimeter.

The actual number of gauges required is unknown but must be sufficient to average across the spatial patterns of sea level change due to global warming. A crude estimate can be made as an average of not more than 12 gauges for each of 5 ocean basins for a total of 60. The design of the network should take into consideration model predictions of the spatial change of global sea level and vertical land motion. The location of gauges should also be such as to minimize the effects of coastal currents and winds which may also change with global warming. Positioning of the tide gauges in an earth reference system requires the combined use of VLBI and GPS. When possible it will be beneficial to use existing tide gauge stations with long consistent records.

A TOPEX/POSEIDON quality altimeter would allow resolution of the spatial pattern of sea level change. It could also result in a reduced requirement for geocentrically positioned tide gauges. However, reduction would be unwise until both an altimeter is guaranteed in the long-term and any questions of maintaining the integrity of altimeter orbits in the earth reference system are resolved.

Deficiencies. The suitability of existing and potential tide gauge sites should be studied in the context of designing a network to measure estimated patterns of global sea level change. In addition, expert agreement needs to be obtained on the best methodology for establishing a geodetic geocentric reference frame and siting the tide gauges in it.

## B. Immediate Subgoals and Needed Observations

Recommended subgoal priority. The OOSDP ranked the subgoals using as a guide the general criteria of impact and feasibility. Higher priority is assigned to subgoals for which the observations of highest impact are currently attainable, implying that the goal likely will be met. To some extent priority has been given to subgoals where immediate attention is needed to continue research systems of proven utility (for example, elements of the TOGA observing network) or there is a serious environmental concern (for example, global sea level change).

Four ranks of priority were used. Within a numbered rank, the absolute position of one subgoal relative to another is unsure. Note that the Panel gives priority to meeting all of the subgoals: their selection is a reflection of that priority.

| Subgoal | | Ranking |
|---|---|---|
| 1a | SST | 1 |
| 1b | Wind and wind stress | 1 |
| 1c | Heat and freshwater air-sea fluxes | 2 |
| 1d | Surface carbon fluxes | 2 |
| 1e | Ice | 2 |
| 2a | Upper ocean monitoring | 2 |
| 2b | Pacific ENSO prediction | 1 |
| 2c | Global seasonal-interannual prediction | 4 |
| 3a | Global inventories | 3 |
| 3b | Circulation and transport | 4 |
| 3c | Sea level change | 1 |

Priority of observational elements. The ranking of the subgoals provides guidance on the order of priority that should be given to the implementation of the elements of the observing system. Table VIII.B.2-1 lists the subgoals in order of their stated priority (within each rank the order is in numerical and alphabetic order) and also lists all the observing system elements of category 1 (elements of existing operational systems) and category 2 (elements that are to be added now to constitute the initial observing system). Elements of category 3 (enhancements of the initial system to be added when feasible) are not shown.

For each subgoal the table shows only those category 2 observational elements which have not been already introduced in support of subgoals of higher level in the table.

Table VIII.B.2-1. Summary of existing operational elements and elements to be added now to complete the initial observing system recommended for each subgoal. The subgoals are ordered by priority assigned by the OOSDP. Elements to be added now in support of a subgoal may contribute to other subgoals, as indicated, illustrating the complex relations between the various subgoals and observational elements.

| Subgoal | Priority or Rank | Elements of existing operational systems (category 1) | Elements to be added to constitute the initial observing system (category 2) | Lower ranked subgoals supported by element | Higher ranked subgoals and elements thereof that support this subgoal |
|---|---|---|---|---|---|
| 1a. SST, SSS | 1 | global satellite SST (AVHRR)<br>VOS reporting SST<br>moored and buoy SST | 1) use of ATSR<br>2) SST on quality VOS<br>3) SST on more drifters<br>4) SST & SSS on TAO | 1b, 1c, 1d, 2a, 2b, 2c, 3b<br>1b, 1c, 1d, 2a, 2b, 2c, 3b<br>1b, 1c, 1d, 2a, 2b, 2c, 3b<br>1b, 2b | |
| 1b. Wind and wind stress | 1 | VOS met observations<br>NWP model analyses<br>SLP from buoys<br>altimeter wind speed | 5) scatterometer<br>6) TAO array winds<br>7) SLP in S. Hemisphere<br>8) Improvement of VOS winds | 1c, 1d, 2a, 2b, 2c, 3b<br>2b<br>1c, 1d, 2a, 2b, 2c, 3b<br>1c, 1d, 2a, 2b, 2c, 3b | 1a |
| 2b. ENSO prediction | 1 | operational SST and wind analysis<br>in situ sea level | 9) T(z) from VOS<br>10) T(z) from TAO<br>11) V(z) from TAO<br>12) precision altimeter | 2a<br>2a<br><br>2a, 2c, 3b, 3c | 1a, 1b (especially elements 4 and 6, TAO array SST and winds) |
| 3c. Global sea level change | 1 | nil | 13) high quality geocentrically located tide gauges | | 12 (precision altimeter) |
| 1c. Surface heat and water fluxes | 2 | operational wind and SST analyses<br>NWP fluxes<br>existing VOS met observations<br>satellite radiation & precipitation<br>met buoy data | 14) improved VOS met observations<br>15) in situ radiation<br>16) regional flux verification (buoys) | 1d, 2a, 3b<br><br>2a, 3b<br>2a, 3b | 1a, 1b |
| 1d. Surface $CO_2$ flux | 2 | nil | 17) $pCO_2$ from manned VOS<br>18) fluorescence from manned VOS | 3b<br>3b | 1a, 1b, 1c |
| 1e. Sea ice | 2 | sea ice extent & concentration (satellite microwave) | 19) ice drifters<br>20) in situ ice thickness | 3b<br>3a, 3b | |
| 2a. Upper ocean monitoring | 2 | regional upper ocean monitoring | 21) T(z) (global VOS broadcast XBTs)<br>22) T(z) (S. Hemisphere supply vessels)<br>23) T(z) (autonomous floats) | 3a<br>3a<br>3a, 3b | 1a, 1b, 1c, 12 (precision altimeter) |
| 3a. Global inventories | 3 | nil | 24) time series T, S, and carbon<br>25) repeat sections for water mass formation | | 1e, 2a |
| 2c. Global seasonal to interannual prediction | 4 | nil | nil | | 1a, 1b, 2a, 2b, 12 (precision altimeter), 21 (VOS T(z)), 23 (T(z) from autonomous floats) |
| 3b. Global circulation and transport | 4 | national long-term operational sections, river discharge monitoring | nil | | 1a, 1b, 1c, 1d, 1e, 12 (precision altimeter), 23 (T(z) from autonomous floats) |

To show the extent to which category 2 elements introduced to meet higher priority subgoals can contribute to those of lower priority, the table shows the subgoals of lower order in the table to which each element contributes. Similarly, the table shows higher ranking subgoals and/or the category 2 observational elements (numbered) by which each subgoal is supported. The contribution made by the category 2 observational elements required for the subgoals of higher rank to a number of subgoals of lower rank is striking.

Note again that the table does not include elements of category 3 (elements to be added later as feasible), which also are essential if the ocean observing system for climate is to satisfy the full requirements of the subgoals. Some elements were classified as category 3 because they require further research and development; others because of their immediate priority and concern regarding the total cost of the system. For example, the repeat hydrography and the transocean sections of T, S, carbon, and selected tracers have been listed as category 3 even though they are *essential* to attaining subgoals 3a and 3b. They lack some urgency because of the global coverage now being provided by WOCE and because their inclusion would require long-term commitments (at least commitments with repeat terms of five to 10 years) that nations are unlikely to make to an operational observing system at this time.

## C. A Coherent Conceptual Design for the Observing System

The OOSDP is convinced of the need for ongoing self evaluation as part of the system. The functions of the evaluation unit (Section VII.D) which must be carried out include detailed monitoring of performance, assessment of technical developments, and examination of strategic tradeoffs. Support for these activities is essential.

Additional activities are needed to help ensure a coherent, effective ocean observing system for climate, the common module of GOOS and GCOS. Here we concentrate on the delivery of the information and products that together will fulfill the general goal (i.e., provide the "whole" ocean observing system for climate). The basis for this final step will be a suite of processing activities which ingest observations from many sources and output high quality, useful products for the users of this observing system.

These may be thought of as processing pathways from measurements to user products. The effectiveness and efficiency of these connections is of fundamental importance, and it is equally critical that these processing pathways are constructed and presented in such a way that the users of the products are able to appreciate and understand that the basic observing system is the fundamental strength of the system.

While there will be many pathways from observations to products, we will try to represent the essence of the process through three streams of activity.

1) Climate assessment. One of the principal motivations for a global climate observing system is the possible change in the earth's climate due to anthropogenic effects (e.g., the enhanced Greenhouse effect). The OOSDP response to this issue is to recommend the establishment of an ongoing climate assessment activity (center or centers) with the principal aim of providing regular, state-of-the-art assessments of the state of the (ocean) climate.

2) Model development and validation. A theme through the discussion of observing elements in Section V is the need to include models in network design, quality control, interpretation of data, and in the projection of information in space and time (mapping and forecasts). One responsibility of the observing system designers is to ensure that models reliably and faithfully represent the relevant oceanic processes.

3) Numerical ocean prediction. TOGA and related activities have brought oceanography to the point where useful climate forecasts (seasons to several years) are now thought to be attainable. The OOSDP recommends that forecasting capability be achieved through facilities/activities dedicated to the processing of relevant data and producing forecasts and related applied products. Initially, the focus will be on seasonal to interannual prediction but in time may evolve into a more general ocean prediction capability.

Note that each of these activities will depend to some extent on the total information in the observing system data base, not just on elements dedicated to the particular goal or phenomenon. It is this cross-utilization of information that provided the strength in the total conceptual design (e.g., Table VIII.B.2-1). It will be the responsibility of the bodies charged with scientific oversight of GOOS and its modules to continually review and evaluate the system, and to suggest changes which improve its scientific products and processing and which maximize the economic and social benefits.

# SCIENTIFIC DESIGN FOR THE COMMON MODULE OF THE GLOBAL OCEAN OBSERVING SYSTEM AND THE GLOBAL CLIMATE OBSERVING SYSTEM:

# AN OCEAN OBSERVING SYSTEM FOR CLIMATE

## I. INTRODUCTION

### I.A. The Requirement: An Ocean Observing System for Climate

The climate system of Earth has experienced natural variability ranging from the warmth of the Cretaceous to the cold of the ice ages. During most of their tenancy on Earth, humans have not been just passive spectators of climate variability—witness changes to continental land surfaces by primitive peoples. Today, however, human activities increasingly are recognized as a likely source of profound influence on the nature, timing, and extent of climate change. Through such activities as worldwide burning of fossil fuels and increasing gaseous emissions from agricultural practices, humans have become active participants in changing climate.

As population increases, as predictions of climate variations become feasible, and as evidence of human-induced climate change increases, policy makers around the world seek information to guide them in their decisions on matters related to climate. Vital issues of economic and social well-being are involved. Several international scientific programs have been established to address the concerns and to develop scientific information on climate change that is needed to provide effective guidance to policy makers. Among these are the Tropical Ocean and Global Atmosphere (TOGA) Programme, the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), and the Global Energy and Water Cycle Experiment (GEWEX).

The Second World Climate Conference, held during November 1990 in Geneva, Switzerland, considered the issue of human-induced greenhouse warming and other global changes. The first decade of work under various global programs, such as the World Climate Programme, and the First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), entitled Climate Change: The IPCC Scientific Assessment (IPCC, 1990), were discussed. The Conference attendees agreed that scientific conclusions set out in the IPCC report reflected the international consensus on scientific understanding of climate change and that there was a need to reduce the uncertainties in climate prediction by research on how the climate system works. One priority research area was the ocean, including the physical aspects of the ocean and the interactions of the ocean and atmosphere. The Conference participants further agreed that a system of observations on the various components of the climate system, including a global ocean observing system, should be developed to monitor climate changes more effectively.

The IPCC report assessed the present state of the scientific information on climate change. It identified the oceans as one key area of scientific uncertainty for further research and stated that "the oceans play a central role in shaping the climate through three distinct mechanisms": the absorption and exchange of carbon dioxide with the atmosphere; the exchange of momentum, heat, and fresh water with the atmosphere; and the storage of heat absorbed at the surface in the depths of the ocean. The exchange of energy between the ocean and the atmosphere and between the upper and deep layers of the ocean, and the transport of energy within the ocean were identified as processes that control the rate of global climate change and the patterns of regional change. The report defined these as areas for further research. In addition to studying oceanic processes and the coupling of the ocean and the atmosphere, the IPCC report pointed out that the ocean circulation is not well observed and that, therefore, "there is less confidence in the capability of models to simulate the controlling processes." The report recommended "the establishment of a global ocean observing system to measure changes in such variables as ocean surface topography, circulation, transport of heat and chemicals, and sea-ice extent and thickness" and "the development of major new systems to obtain data on the oceans...using both satellite-based instruments and instruments based on the surface, on automated instrumented vehicles in the ocean, on floating and deep sea buoys, and on aircraft and balloons." The IPCC report called for nations to make the necessary financial and resource commitment to the existing programs of the World Climate Research Program (WCRP) and the International Geosphere-Biosphere Program (IGBP).

The goal of the international global change programs ultimately is to be able to understand and predict climate changes, especially those caused by human activities. The scientists who planned WOCE, TOGA, and other global change research programs developed their experiments to address two basic needs that will advance our ability to predict climate on time scales of years, decades, or centuries: more ocean observations and improvements in ocean modeling. TOGA deals with changes over time scales from seasonal to as long as several years. The best known example of climate prediction concerns the onset of El Niño and the associated El Niño-Southern Oscillation (ENSO) events as a result of TOGA research. The intensive period of TOGA tropical ocean observations were started in 1985 and continued through 1994. A global data set for WOCE was started in 1990 and is planned to continue through 1997. WOCE, as well as JGOFS, ultimately are aimed at understanding and prediction of longer-term decadal climate change. An example of longer-term climate variability in the coupled ocean-atmosphere system is to be seen in the relationship between sea-surface temperature in the Atlantic and rainfall in the Sahel (Folland et al., 1986). Analysis of global sea surface temperature (SST) shows that Sahel rainfall is correlated with a mode of global SST variability which is greatest in the Atlantic and asymmetric to the equator. Climate predictions which may be possible as a result of these research programs require a global observing system and climate models, which must include sophisticated representations of the processes governing the interaction between the ocean and atmosphere. Scientists and policy makers recognize that the present state of ocean and coupled ocean-atmosphere models is not advanced sufficiently to provide the needed results, primarily for two reasons.

First, the data base of ocean observations is too sparse to ensure that the important physical and biogeochemical processes are identified and understood and is inadequate to properly test and validate ocean models. Second, because the spatial and temporal scales of ocean processes demand large computing capacities, advances in modeling techniques, coupled with improvements in computing power, are needed to reproduce the ocean circulation accurately. Thus, the observational data base on the oceans must be substantially increased with long-term systematic measurements, and ocean modeling must be advanced, before the present state of the ocean and of ocean-atmosphere interactions—and of climate—can be portrayed adequately. An adequate baseline is essential as background to detection and prediction of changes, and the better the baseline the better the design of the sampling scheme to detect changes. However, the Ocean Observing System Development Panel (OOSDP) feels strongly that the baseline is in many instances quite sufficient to design an ocean observing system for climate; improvements can come in the future, it need not be perfect at the outset.

The ocean provides the opportunity for monitoring climate changes that may be difficult to observe in the atmosphere with its great natural variability on short time scales. For example, one may expect to observe only in the ocean the integrated effect of the small changes in air-sea fluxes of heat (and maybe fresh water) that will result from increasing greenhouse gas concentrations during the next decades. Of course, the ocean exhibits changes on all time scales, some of which can be related to longer-term changes in the atmosphere. For example, during the late 1950s and early

1960s, cooling of the atmosphere was accompanied by a salinity anomaly in the North Atlantic, which in turn resulted in changes in deep water formation (Dickson et al., 1988).

At the present time, it is not possible to account for all of the anthropogenic $CO_2$ that has entered the atmosphere. The missing carbon amounts to approximately 1.6 Gt C/year or 25% of the annual anthropogenic input. The contribution of oceanic processes to this missing carbon is unknown. The problem is exacerbated by observations of a 50% decrease in the rate of $CO_2$ increase in the atmosphere between 1991 and 1994 that remains unexplained. Since inputs have not diminished during this period, the change must be due to an increase in $CO_2$ uptake either by the oceans or the terrestrial biosphere. Global and systematic measurements of variables related to the $CO_2$ exchanges would have been invaluable in explaining this change and the future evolution of atmospheric $CO_2$ concentrations.

There are many reasons why a global ocean observing system should be designed now. It is not now possible to attribute observed warming during the 1980s specifically to anthropogenic effects or to natural variability. If, as most scientists believe, global warming is actually taking place due to increased greenhouse gas concentration, a system of monitoring and model development is necessary to detect it and its rate of occurrence. This will allow society to have sufficient basis and lead time to intelligently plan ameliorative actions to deal with undesirable manifestations of climate change. For example, the question of how sea level will respond is crucial to many nations and the debate will not be settled without an adequate observing system.

Development of models for climate change prediction and analysis depends on more complete and more accurate data sets. Although global change research programs are, or will be, collecting data, such research programs are time-limited; they are not designed for the purpose of providing systematic observations beyond their scheduled completion dates. Some of these data sets likely will be needed as part of an operational observing system; if this is to happen we must define and begin implementation of the system in time to continue such observations as the research programs terminate.

The present state of technology makes the implementation of a truly global ocean observing system feasible now, although ongoing and future developments should greatly improve its capability, efficiency, and economy. Technologies for use now include remote sensing by satellites and a large array of in situ instruments. Many of these in situ measurements can be made by expendable equipment. We are rapidly developing additional smart, autonomous expendables that return data via telemetry. That avenue of development, together with unmanned, observing vehicles and integrating technologies, should reduce our reliance on research vessels even more in the future.

To assist in the planning and development of a Global Ocean Observing System (GOOS), the Committee on Climatic Changes and the Ocean (CCCO) of the Scientific Committee on Oceanic Research-Intergovernmental Oceanographic Commission (SCOR-IOC) and the Joint Scientific Committee (JSC) of the International Council of Scientific Unions-World Meteorological Organization (ICSU-WMO) jointly established the OOSDP in 1990. This Panel also was charged with the initial design of the ocean component of the Global Climate Observing System.

> The Panel was given the task of formulating a "conceptual design of a long-term, systematic observing system to monitor, describe, and understand the physical and biogeochemical processes that determine ocean circulation and the effects of the ocean on seasonal to decadal climate changes and to provide the observations needed for climate predictions."

# I. INTRODUCTION

This is the final report of the OOSDP. It expresses the conceptual design of the common module of GOOS and the Global Climate Observing System (GCOS). It is understood that the OOSDP will be succeeded by a scientific panel of GOOS and GCOS to monitor and refine the design of this module. It was agreed by GCOS and GOOS that the implementation of this module will be primarily the responsibility of GOOS.

Throughout this report the common module of GOOS and GCOS is referred to as the ocean observing system for climate, or simply as the observing system.

The OOSDP has included in its considerations those observations within the coastal ocean needed for a global climate observing system. However, the Panel has not considered observations, within the coastal ocean or elsewhere, that may be needed to define the impacts of climate change on the coastal ocean. Our focus has been on large-scale climate changes; we have not planned for observations needed to monitor, detect, understand, or predict changes in regional climate regimes.

## I.B. Uses and Societal Benefits of the Ocean Observing System for Climate

A comprehensive ocean observing system for climate will provide information for a variety of applications, some relatively well understood, others less well formulated. The former have strongly influenced the design of the observing system presented here. For the latter, although the design criteria may be less clear, certain ocean measurements can be seen as required at this time. At a later date, the designers will be able to better define the full suite of required observations using both information already gained from the observing system as well as from the ocean climate research programs of the WCRP and the IGBP.

This section presents some illustrations of applications of the existing ad hoc ocean observing system and of the future observing system for monitoring, detection, understanding, and predicting ocean and climate change. This includes some discussion of economic benefits.

A distinction, sometimes subtle, between monitoring and detection of ocean and climate change is made in this document. Monitoring usually involves the regular, routine plotting or mapping of available measurements of a particular field. This product is then either released without further interpretation (say by an operational agency), or used in conjunction with other information for, say, an indication of monthly to interannual climate trends. In most cases the product is a time series of a particular field (for example, the mean SST in a particular region, or the position of a major current or front). Detection, on the other hand, usually involves a more sophisticated post-processing and interpretation of information for the purposes of identifying change. As an example, the Comprehensive Ocean Atmosphere Data Set (COADS) has been analyzed extensively in the search for trends associated with greenhouse-induced climate change. The distinction between monitoring and detection is not critical for the observing system design of this report, but it is useful to distinguish the regular, routine activities which involve relatively simple processing of data into products from those which require a more substantial analysis. The former activity is already commonplace in many centers (often attached to meteorological agencies) but the latter is mainly restricted to research.

The understanding and prediction aspects of the OOSDP terms of reference also warrant some comment. The observing system is not a research program but, like the World Weather Watch (WWW), will provide baseline data that, when combined with data collected through research programs, will contribute to improved understanding of the ocean and climate. In turn, this new knowledge will be used to improve and optimize the observing system. Research programs will supplement the observing system data base and use the observing system to provide data communications and management, much as is done today with the Integrated Global Ocean Services System (IGOSS). For many people the prediction of ocean and climate change is the ultimate goal. While in some areas successful ocean climate predictions are feasible, this is not in general the case. For the foreseeable future prediction will be just one facet influencing observing system design and an appropriate emphasis on monitoring, detecting, describing and understanding climate change is required.

### I.B.1. Ocean monitoring on climate scales

An ocean observing system for climate will provide data to establish the climatology of the ocean, including the statistics of its variability. Within this framework it will enable monitoring of natural and anthropogenic climate change. An example of the requirement for this may be seen in a recent review by Folland et al. (1992) of the adequacy of existing estimates of a basic climate variable, global SST. They show deficiencies in existing analyses, especially in the Southern Ocean where in situ data are sparse. In general, analyses of long-term trends in historical data may be adversely affected by changes in measurement techniques and/or adequate quality control over the full length of the record.

Climate monitoring is an essential element of many national meteorological services. In the absence of an observing system, arrangements for gathering and analysis of some ocean data relevant to climate have been achieved through the WWW and IGOSS. For the last several years a selection of products have been published in the IGOSS Products Bulletin (available from Bundesamt für Seeschiffahrt und Hydrographie, Hamburg, Germany). Two examples of monitoring ocean and climate change are discussed here but similar activities occur at many centers.

The Japan Meteorological Agency (JMA) has been routinely gathering and analyzing ocean data, particularly that of the Northwest Pacific, for many years. JMA produces SST, subsurface temperature and surface current maps based on data circulated on the Global Telecommunication System (GTS) through IGOSS (refer to Appendix II) and on data collected by various Japanese agencies. The data are quality controlled using a mix of subjective and objective tests and mapped onto a regular grid (2° for basin and global products, but very much finer for the local region). These products are disseminated to interested users, such as local fishing fleets, in a variety of ways and are published in a Monthly Ocean report (available from the El Niño Monitoring Centre of JMA). Figure I.B.1-1 shows an analysis of sea surface current in the western North Pacific for the period 21-30 September 1993. The measurement techniques include acoustic Doppler profilers aboard merchant and research vessels, geomagnetic electrokinetographs (GEKs) deployed on research vessels and drift estimates by merchant ships and surface buoys. Such products are useful for ship routing but also provide information on the ocean circulation on climate scales (e.g., the Kuroshio).

Oceanographic data are being increasingly used in routine monitoring of climate change on monthly to interannual time scales. As an example, the Bureau of Meteorology Research Centre (BMRC) runs global SST and subsurface temperature analysis systems, primarily to monitor tropical ocean variability, drawing on data available through IGOSS, the Global Temperature and Salinity Pilot Project (GTSPP) and various other sources such as the TOGA Tropical Atmosphere-Ocean array. Figure I.B.1-2 shows a longitude versus time plot of the anomaly in the depth of the 20°C isotherm along the equator in recent years. The build up to the 1991-1992 warming in the central and eastern Pacific and the establishment of cold La Niña conditions in early 1994 are both clear in such analyses. This product, together with various other analyses, form an integral part of the regular (monthly) climate analysis and assessment of the Australian Bureau of Meteorology National Climate Centre and are part of the collective information used to form climate prognoses and seasonal outlooks by the Bureau. Such activities are also routine at many other centers. For example, the Climate Analysis Center of the U.S. National Meteorological Center issues ENSO advisories and climate outlooks in their Climate Diagnostics Bulletin and through telemail services. At this time both research and operational agencies are involved in such activities.

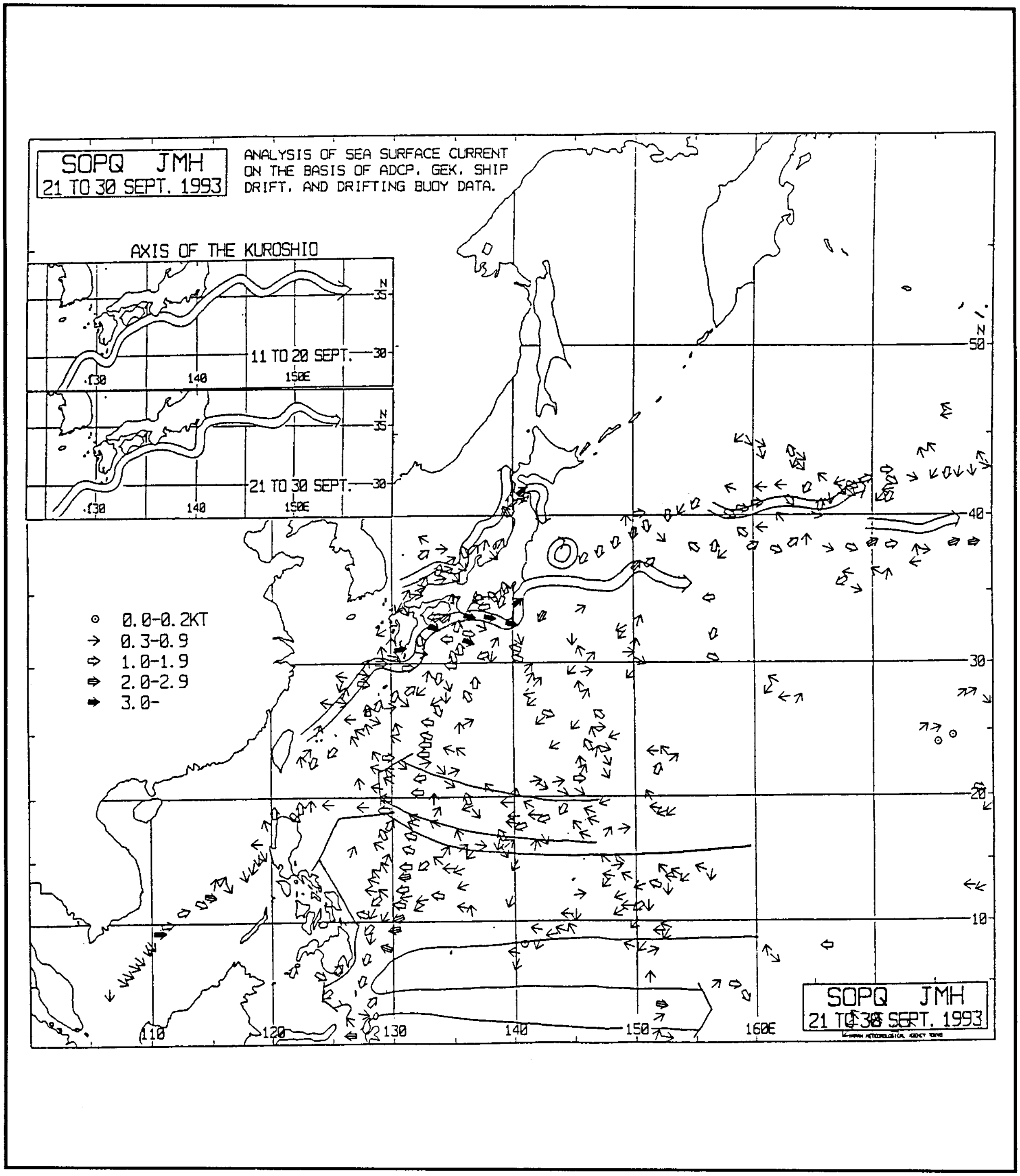



Figure I.B.1-1. Surface currents in the western North Pacific for the third ten-day period in September 1993. Small arrows indicate currents measured with acoustic Doppler current profilers, GEKs deployed from research vessels, and ship drift by merchant ships and drifting buoys. Major currents such as the Kuroshio and the North Equatorial Current are denoted by larger open arrows. (From the September 1993 Monthly Ocean Report of the El Niño Monitoring Center of the JMA.)

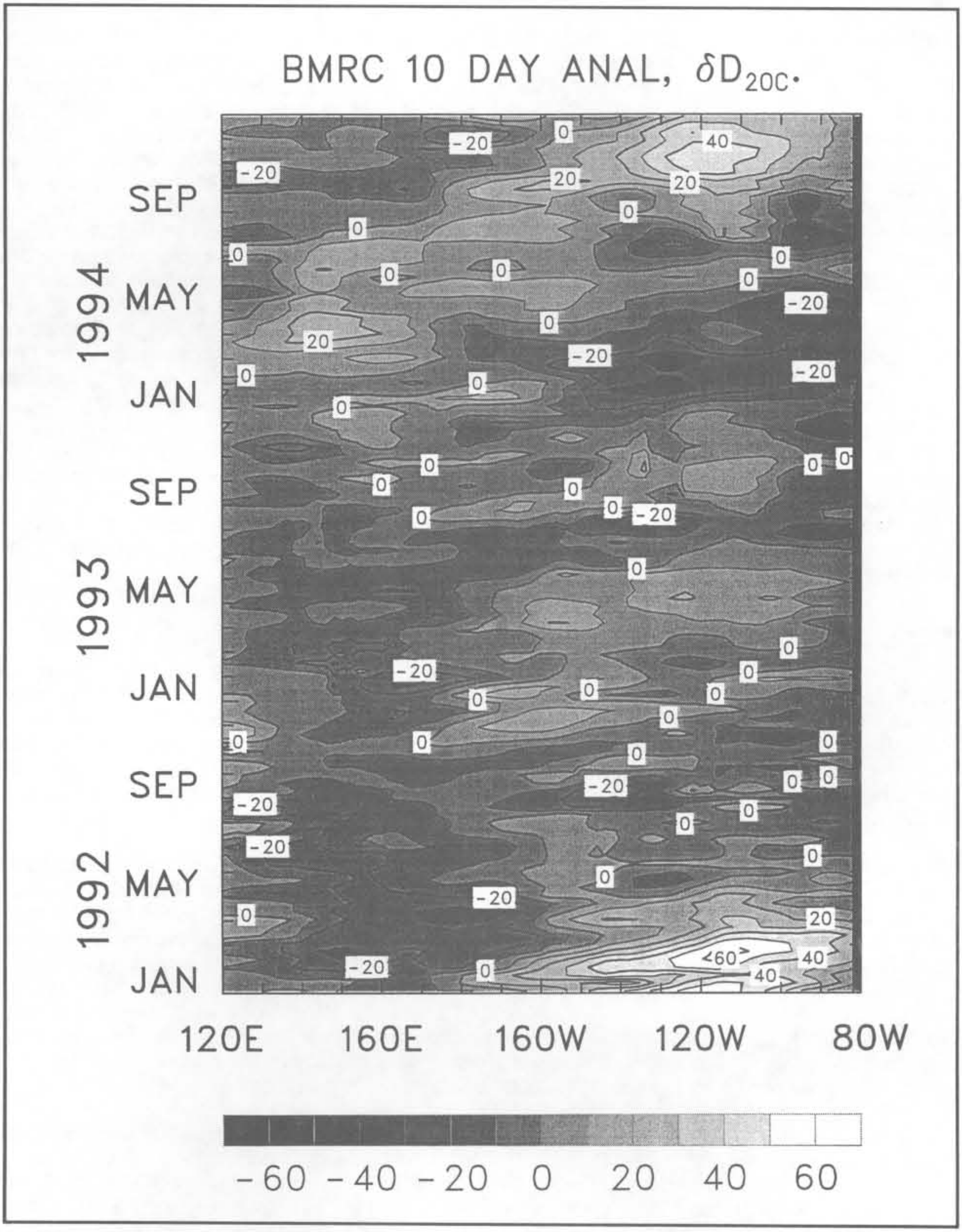



Figure I.B.1-2. Longitude versus time for the depth of the 20°C isotherm along the equator in recent years.

For the longer term analysis of climate change, the COADS has been widely used. It is a large collection of observations taken from merchant, navy, fishing and research vessels, fixed and drifting buoys and coastal stations. Through a cooperative effort among National Oceanic and Atmospheric Administration (NOAA)/Environmental Research Laboratories (ERL), NOAA/ National Climate Data Center (NCDC) and National Center for Atmospheric Research (NCAR) these observations have been combined into a data set spanning 1954-1992. Popular COADS products include the set of original observations with reported variables (winds, SST, air temperature, sea level pressure, clouds, etc.) and monthly statistics for 19 observed and computed variables in 2° latitude by longitude boxes. Although the original COADS release in 1985 was restricted to 1854-1979 (Woodruff et al., 1987), the subsequent release in 1993, and others planned for the future, will serve to expand the time series to include new data and improve data quality. COADS is an important input for the upcoming global atmosphere reanalysis projects.

Other existing ocean products are the sea ice analyses and forecasts on global, regional, and local scales produced by the U.S. Navy/NOAA Joint Ice Center (JIC). These global analyses for both the Northern and Southern Hemispheres consist of a determination of the ice edge, the concentration of the ice, leads in the ice, and an estimation of the age of the ice. Regional ice analyses are produced twice per week for the Bering, Chukchi and Beaufort seas. Local-scale analysis are available for ships operating in the Antarctic during the austral summer. The JIC produces seven-day and 30-day ice forecasts and long-range outlooks. The seven-day forecasts are produced weekly for the eastern and western Arctic and give the expected position of the ice edge. The 30-day forecasts are produced twice monthly for the ice edge position and ice concentrations in the eastern and western Arctic. Long-range outlooks forecast the expected severity of ice conditions and are verified approximately 90 days after issuance.

### I.B.2. Examples of detection of ocean changes on climate scales

That observations of the surface ocean can be used to monitor climate change is illustrated by the examples provided in the previous section. That interannual climate change occurs in the upper ocean of the tropical Pacific is discussed in the next section in the context of ENSO. Although climate change in the deep ocean cannot be defined in such detail, it is known to exist where there are adequate observations for its detection. In particular, in the North Atlantic, which is by far the best observed of the ocean basins, the signature of climate variability on interannual to decadal time scales can be found in the historical records.

Historical hydrographic data were assembled by Levitus (1982) to provide a global climatological description of the mean fields of temperature, salinity, and density. For most of the globe the data set can only marginally define this "mean" climatology, which has been used as the basis for many large-scale ocean models. Moreover, the sharpness of major features such as the Gulf Stream are greatly smoothed by inadequate sampling in space and time. Nevertheless, Levitus (1989a, b, c, 1990) was able to show that substantial differences exist in the deep North Atlantic based on data collected during the five-year periods 1955-1959 and 1970-1974. For example, Figure I.B.2-1 shows that the temperature at 1000 m varied by almost a degree in some regions. However, these differences may be due in large measure to the data distribution or analysis techniques, emphasizing the need for a long-term, systematic data collection system.

Similar variability can be seen in the analysis by Roemmich and Wunsch (1985) of two high quality sections taken along 24.5°N and 36.5°N in 1981 and their comparison with sections at almost identical latitudes occupied during the International Geophysical Year (IGY), 1957. The temperature, salinity, and density along the sections (for example, Figure I.B.2-2) show differences of the same order as seen by Levitus in the historical data. However, although Roemmich and Wunsch found some differences in the details of the circulation between 1957 and 1981, their analysis using inverse techniques shows little change in the Gulf Steam transport, thethermohaline circulation and, perhaps most significantly for climate purposes, the meridional heat flux.

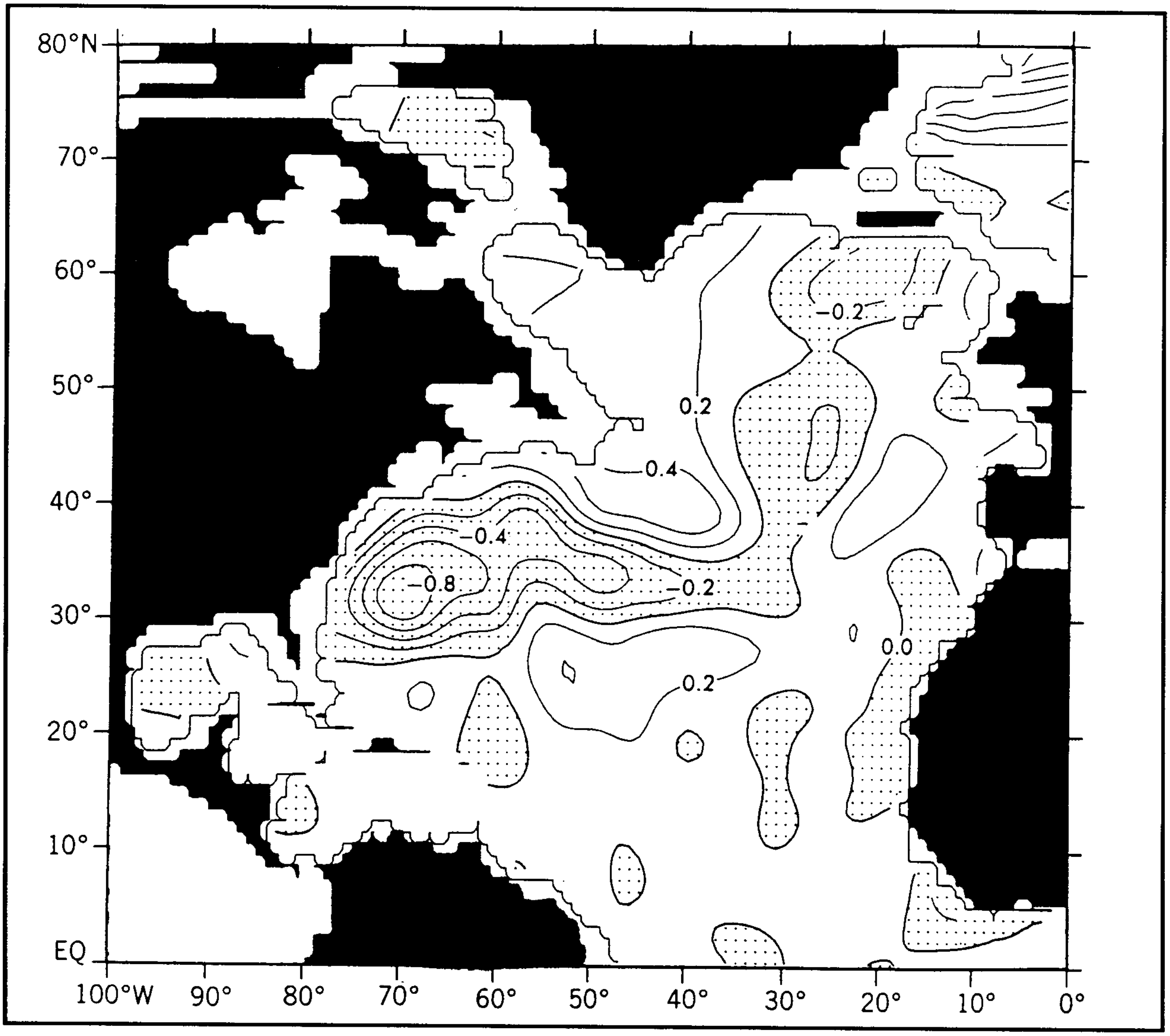



Figure I.B.2-1. Temperature difference (°C) for 1970-1974 minus 1955-1959 at 1000 m depth. Dot shading indicates negative values (Levitus, 1989a).

Long-term variations in winter SST in the North Atlantic have been identified in 90 years of COADS records studied by Deser and Blackmon (1993). Using empirical orthogonal functions (EOFs), they identified two modes of variability: 1) a long-term increase in temperature over most of the basin and 2) a dipole structure in the western basin in which SST anomalies off Newfoundland are out of phase with those off the U.S. east coast. The dipole EOF has a 10-12 year time scale and appears to be linked to decadal variations in sea ice extent in the Labrador Sea. Positive sea ice anomalies lead negative SST anomalies off Newfoundland by two years, suggesting that the advection of low salinity surface waters may be involved. Interdecadal change in atmospheric pressure over the North Atlantic (and thus long-term patterns of weather over Europe) may occur in part in response to SST anomalies in the North Atlantic (Kushnir and Held, 1994).

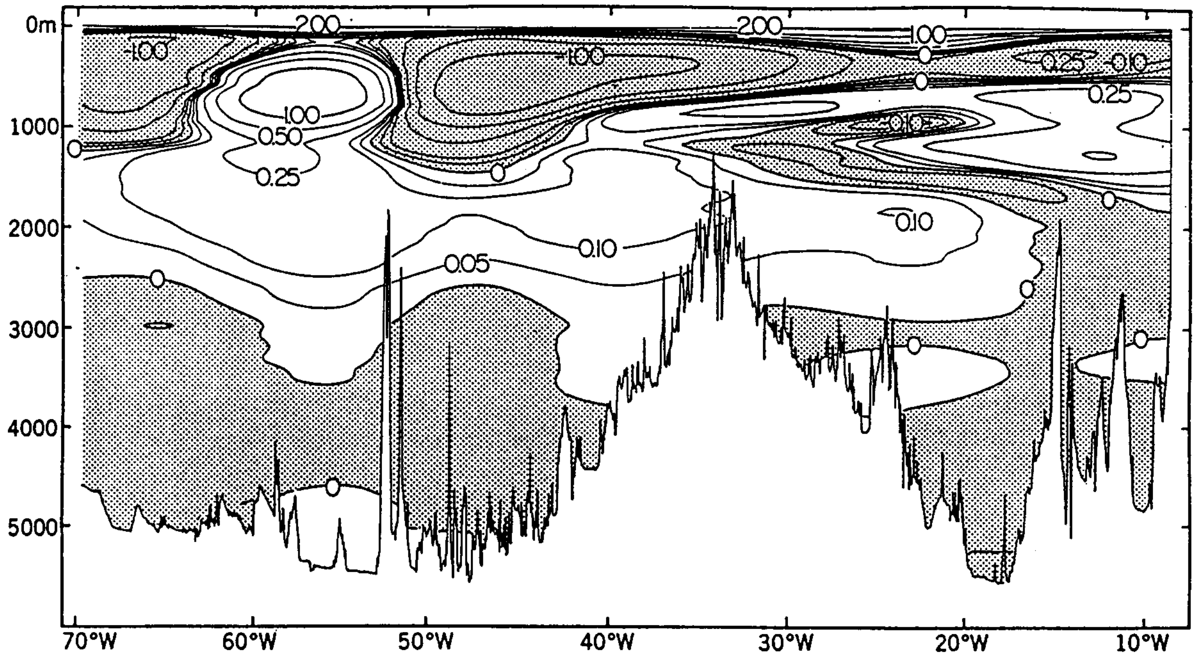



Figure I.B.2-2. Temperature difference as a function of depth along 36.5°N between 1957 and 1981. Units are °C and shading shows negative values. Redrafted from Roemmich and Wunsch (1984) by Levitus (1989b).

The same process is indicated in another North Atlantic climate signal described by Dickson et al. (1988). They show that the "Great Salinity Anomaly", a freshening of the upper 500-800 m, propagated around the subpolar gyre over a period of about 14 years, leaving the region north of Iceland in the mid-to-late 1960s and returning to the Greenland Sea in 1981-1982. Although the Great Salinity Anomaly can be described as a largely advected event carried by the mean circulation of the subpolar gyre, its description comes at a time of increasing speculation that changes in the upper ocean fresh water content of the northern North Atlantic can lead to climatically significant changes in the rate of deep convection and the oceanic meridional heat flux (Weaver et al., 1991; Weaver et al., 1993; Marotzke, 1991).

Interannual variability in the top 1500 m of the central Labrador Sea is clearly seen in the hydrographic data taken from Ocean Weather Station (OWS) Bravo during 1964 to 1973. Lazier (1980) showed that while over this period the deep waters became slightly saltier the upper ocean became fresher, especially during the passage of the Great Salinity Anomaly, until deep convection occurred in the early 1970s. Although OWS Bravo was abandoned in 1973, some hydrographic data has been collected in the central Labrador Sea since that time. Figure I.B.2-3 shows that the salinity and temperature of the waters between 1000 and 1500 m have continued to vary. Since variability in the Labrador Sea at these depths is primarily the result of deep convection (J. Lazier, personal communication), it is an indication of water mass formation and changes in the thermohaline forcing.

It will be impossible to observe the anticipated changes in the flux of heat into the ocean from increasing greenhouse gas concentrations. This is estimated to be of the order 2-4 W/m$^2$ for doubling of atmospheric carbon dioxide, which is much smaller than the uncertainty to which the heat flux is presently known or likely to be determined in the foreseeable future. However, over a long enough period of time, the net effect of such a change in the heat flux will result in a measurable change in the temperature of the full-depth ocean. Similarly, on decadal time scales the oceanic uptake of anthropogenic carbon dioxide should be observable. The prescribed observing system will provide the required measurements.

Where repeat measurements have been made in the ocean below the mixed layer, as illustrated by the examples given above, significant changes have been observed in the temperature and salinity structure. While the causes and dynamical significance of the variability observed are still a matter of scientific discussion, it is clear they represent changes to the ocean environment that are certainly not unique globally and which can only be put into context through the select systematic observations of an observing system. As with variability in the upper ocean, the understanding, interpretation, and possible prediction of major natural or anthropogenic changes will be possible only with the establishment of a full-depth ocean climatology. This will not be established by experiments such as WOCE, which are of limited extent compared to the time-scale of climate change in the full depth ocean.

## I.B.3 Approaches to climate prediction

Deterministic climate prediction. When considering the prediction of climate change it is useful to distinguish between deterministic and probabilistic predictions. In deterministic climate prediction which is often called "prediction of the first kind", the timing of an individual event or phenomenon is forecast on the basis of knowledge of an initial state of the system which must be determined by observations. Even if knowledge of the physical system was complete and models to describe it were available, forecasts of the climate at a particular time in the future would be imprecise for two reasons. First, the initial state of the system will only be known to a certain accuracy. A number of forecasts may be made using initial conditions that vary within observational uncertainty and a statistical forecast made on the basis of the ensemble of results. Second, the forecast of climate change is only deterministic to the extent it can describe certain "average" properties of the future climate; that is, an ENSO forecast may indicate that a certain month in the future will be cold or wet, but give little or no information about a particular day.

The tropics provide a unique opportunity for climate predictions on time scales of seasons to years because, in contrast to mid and high latitudes, the mechanisms controlling short-term climate variations have a known significant predictable element. The circulation and temperature in the upper layers of the ocean in the tropics respond rapidly to changes in the wind. The resulting basin-scale changes in sea surface temperature are coupled to changes in global atmospheric circulation and associated rainfall distribution, leading to floods in some areas and drought in others. This direct coupling between the tropical oceans and atmosphere is the key to potentially successful climate predictions on time scales of seasons to years.

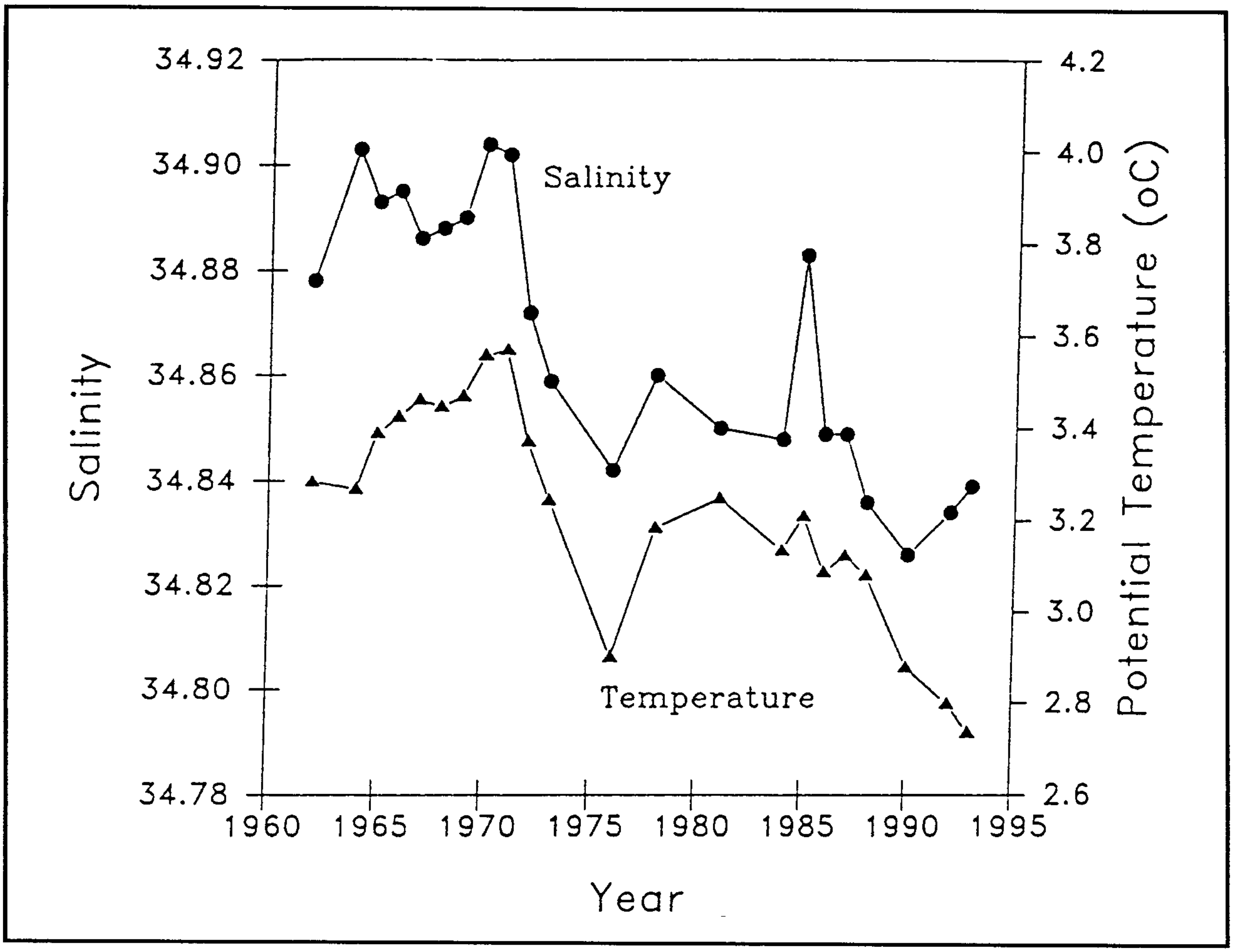



Figure I.B.2-3. Average potential temperature and salinity over the 1000- to 1500-dbar pressure interval in the Labrador Sea. From 1964 to 1970 the data are from Ocean Weather Station Bravo at 56.6°N, 51°W, where about two stations per week were taken. In subsequent years the data are from a variety of cruises in the central Labrador Sea (provided by J. Lazier).

During the past decade a large number of experimental coupled ocean-atmosphere models have been developed for the purpose of studying and predicting tropical interannual variability. These have included the relatively simple "intermediate" coupled models (e.g., Zebiak and Cane, 1987; Kleeman, 1993), the hybrid coupled models in which the atmospheric component is simple but the ocean component is more of the general circulation type (e.g., Neelin, 1990), and fully coupled general circulation models (e.g., Philander et al., 1992; Latif et al., 1993a). The Zebiak and Cane (1987) model has been tested extensively as a predictive tool. The mean state of the ocean model, including the thermal structure, is specified. Anomalies to this mean state are generated by forcing the model with past observed winds, and these anomalies are used to describe the initial state used for prediction. In the coupled, predictive mode the ocean model calculates SST changes for input to the atmospheric model, which in-turn calculates wind changes and so forth. The intensive studies during TOGA have lead to experimental predictions that have demonstrated that some aspects of ENSO events can be forecast up to a year in advance.

Several coupled general circulation models (Philander et al., 1992; Latif et al., 1993a) have shown irregular oscillations in the Pacific Ocean like those observed. However, there remain significant differences, both systematic and in detail, between simulated and observed surface winds and sea surface temperatures. Such models are now being tested for ENSO prediction. In some cases the atmospheric general circulation model (GCM) has been replaced with a statistical model relating SST anomalies to winds (Latif and Flügel, 1991). Several coupled GCM and hybrid models have been tested using only the history of observed wind and SST anomalies to initialize the model (e.g., Latif et al., 1993b). More recently experiments have been conducted in which both wind anomalies and subsurface data have been used to initialize the coupled model (e.g., Ji et al., 1994a). The Ji et al. (1994a) model has been used in an experimental mode for predictions of ENSO events with some success.

The sophisticated ocean models for ENSO prediction that are now under development are capable of assimilating a variety of ocean data (Sarachik, 1991). Until there have been several successful predictions of an ENSO event(s) using such models, it will be difficult to be sure what they must include. However, a basic assumption must be that improved prediction will be obtained from the development and use of models that both better describe the important physical processes and make use of broader data sets for their initialization.

As more in situ data become available for assimilation from the Tropical Atmosphere Ocean (TAO) Array in the Pacific, which is to be completed in 1994, and as observing systems expand more fully into the tropical Indian and Atlantic oceans during the post-TOGA period, better documentation of regional ENSO-related climate impacts and improved real-time analyses for coupled model initialization will be possible. Satellite sea level, wind speed and wind stress retrievals (i.e., from ERS-1 (the Remote Sensing Satellite ESA-1) or TOPEX/POSEIDON) have yet to be fully utilized for initializing dynamical, model-based, short-term climate forecast schemes. Enhanced sampling of ocean-atmosphere variability in the Indian Ocean may lead to improved skill at long lead times because of the fact that surface winds in the tropical Indian Ocean lead those over the tropical Pacific Ocean on intraseasonal to interannual time scales (Barnett, 1983a; Lau and Chan, 1986; Yasunari, 1991). Since model simulations are known to be sensitive to the parameterization of subgrid scale physics (e.g., Miller et al., 1992; Stockdale et al., 1993; Smith and Hess, 1993), improvements in parameterizations in atmospheric models (e.g., cumulus convection, boundary layer processes, etc.) and oceanic models (upper ocean mixing) should improve the ability of models to accurately simulate climate variability and enable the optimization of data assimilation procedures by ensuring compatibility between model dynamics and data fields.

Although the most commonly used validation data set for determining the success of ENSO predictions is the SST anomaly in the equatorial Pacific, for mitigating against the adverse societal impacts of ENSO the success of predicting specific regional tropical and extratropical precipitation and air temperature is more relevant. Already, the atmosphere GCM run at the National Meteorological Center (NMC) for ENSO forecasting is capable of simulating rainfall variability over the continental United States in hindcast mode, with the ability to distinguish the heavy rainfall conditions in the southwest during boreal winter 1982-1983 and 1991-1992 from the drought conditions during boreal winter 1986-1987.

It is known also that extratropical SST anomalies, especially in the North Pacific, and surface temperatures over land are to some extent correlated with ENSO events. However, it is not yet clear to what extent knowledge of SST anomalies outside the tropics would improve climatic predictions using the models now being developed. Outside the tropics, anomalies are known to exist in the structure of the oceanic pycnocline and the associated temperature, salinity, and potential vorticity fields (for example, Armi and Stommel, 1983). The cause and dynamical significance of such variability in the upper ocean and main pycnocline is the subject of various theoretical, numerical, and experimental studies. It is not known whether knowledge of these anomalies could be used in the future for, and be significant in, the initialization of ocean models for deterministic climate prediction. These factors are major aspects of the Climate Variability and Predictability Research Programme (CLIVAR), a new WCRP initiative.

# I. INTRODUCTION

At the shorter climate time scales (weeks to months) there is considerable interest in developing skillful ocean data assimilation and forecast systems. Some of this interest is driven by strategic requirements (IOC, 1991; Peloquin, 1992) and environmental concerns in the coastal regions. Peloquin (1992) gives a general overview of the U.S. Navy ocean modeling and prediction program. For the purposes of this report their prediction systems can be used as typical of applications at shorter time scales. The forecast systems are usually regional (e.g., the Northwest Atlantic), are skillful out to several weeks, and are strongly dependent on the method used for initializing the model (Thompson et al., 1992; Fox et al., 1992). The model data assimilation and forecast systems attempt to delineate features related to mesoscale instabilities (e.g., Gulf Stream meanders and eddies), major currents and frontal locations. The method of initialization and prediction is not straightforward and is in most cases data limited; that is, there are rarely sufficient observations, particularly of the subsurface structure, to reliably initialize a high resolution, eddy resolving model. Nevertheless these systems have demonstrated short range skill relative to persistence out to several weeks (Fox et al., 1992), which is a significant achievement, and are now being implemented in daily Navy operations. There are similar initiatives at several other meteorological and naval agencies.

Probabilistic climate predictions. Sometimes called "prediction of the second kind", this involves the prediction in a statistical/climatological sense on decadal or longer time scales. No attempt is made to use data to define a particular state of the system among possible states as an initial condition. An example of probabilistic climate prediction is the major effort that is being made to provide increasingly reliable estimates of the expected global warming as a result of increasing levels of greenhouse gas concentrations. Depending on the emission scenario used, present predictions are for an increase in the global mean surface temperature of between 1.5°C and 4.5°C during the next century (IPCC, 1992). The simulated rate of change in sea level from thermal expansion as the ocean is warmed ranges from 2 to 4 cm/decade (Wigley and Raper, 1992). The two major causes for the present uncertainty in simulations are lack of knowledge of, and adequate models for, the atmospheric radiation balance (clouds) and the ocean. The great heat capacity of the ocean provides damping of the climate system, a factor that is believed to be the main reason greenhouse gas warming has been kept to levels that are yet to be distinguished from natural climate variability.

The probabilistic prediction of greenhouse gas warming depends on having models that provide good representations of the important processes controlling the climate of the oceans and atmosphere. A basic check on the validity of these models is that they give realistic representations of the ocean circulation, and of its interior and surface fluxes of heat and fresh water. An equally important check is that the models generate climate variability similar to that of the existing ocean. Observations of such variability will only be provided by a long-term, systematic observing system.

At present when using coupled atmosphere-ocean models, in order to prevent a drift towards unrealistic states on decadal time scales, it is necessary to impose artificial corrections to the surface fluxes across the air-sea interface. This is because when the atmospheric and oceanic models are driven independently using what are thought to be realistic surface boundary conditions they describe atmospheres and oceans with inconsistent surface and meridional fluxes of heat and fresh water. The origin of this inconsistency remains uncertain. That the required flux corrections are sometimes as large as the fluxes themselves and vary greatly from one model to another causes concern about the reliability of simulations of greenhouse gas warming.

WOCE will provide an improved description of the global ocean circulation that will provide an important test of ocean models used for simulation of greenhouse gas warming. However, it will only be from the systematic surface and upper ocean measurements from an observing system that the fluxes between the ocean and the atmosphere will be better defined. Atmosphere-ocean fluxes can be estimated from a variety of oceanic measurements (CCCO, 1992). While net fluxes over large regions may best be obtained from deep ocean measurements, it will be through the assimilation of surface and upper ocean measurements in operational ocean models that variations in space and time will be determined. These in turn will be used to test the fluxes provided by atmospheric numerical weather prediction (NWP) models, which at present provide the global estimates. In the tropics this process is already leading to improved coupled models and is providing a basis for improved ENSO prediction.

Coupled atmosphere-ocean models used for greenhouse gas warming simulations can generate climate variability on a variety of time scales including decadal. This variability includes global changes in surface temperature (Stouffer et al., 1994) and in the thermohaline overturning in the North Atlantic (Delworth et al., 1993; Manabe and Stouffer, 1994). While the former shows qualitative agreement with observations over the last century, no oceanic data exist to check the reality of the latter. There are also indications that the degree of greenhouse gas warming over the next few decades depends on the actual oceanic state (Cubash et al., 1992). A long-term goal for an observing system is to establish a record of decadal oceanic variability on which an understanding of its nature and role in atmosphere-ocean exchanges may be based. The possibility of initializing models for long-term climate prediction is only a matter for speculation.

### I.B.4. Successful climate predictions and societal value

The most remarkable progress toward predicting climate change has been in the ability to forecast short-term climate variability associated with the ENSO phenomenon. This progress, mostly achieved over the last decade, has been stimulated by the development of a variety of models used for ENSO prediction; by empirical studies that have better defined the global impacts of ENSO; by theoretical studies that have elucidated the underlying oceanic and atmospheric processes accounting for the predictability of ENSO; and by the establishment of an ocean observing system (primarily in the Pacific) for initializing and verifying models under development for ENSO prediction. Compared to the early 1980s when observational techniques were inadequate to even monitor the evolution of an ENSO event once underway, we are now able to observe day-to-day changes in surface winds, SST, upper ocean thermal structure and ocean currents on a basin scale in the tropical Pacific; and routinely issue experimental forecasts with useful skill at up to one-year lead times.

Models used in ENSO prediction range from purely statistical models to fully coupled dynamical ocean-atmosphere models (see also Section I.B.3). The dynamical models range in complexity from tropical Pacific basin intermediate physics models to global coupled ocean-atmosphere GCMs. Most experience in dynamical forecasting is based on the intermediate class of models which simulate only climate anomalies, thus avoiding problems related to climate drift that often affects coupled GCMs (Neelin et al., 1992). Cane et al. (1986), using an intermediate model, made the first successful forecast of an ENSO one year in advance of the 1986-1987 event. This accomplishment was later reinforced by statistical and hybrid statistical-dynamical model-based forecasts as described in Barnett et al. (1988). The Cane-Zebiak model also successfully forecasted the 1991-1992 ENSO one year in advance (Kerr, 1992). Similarly, despite some empirical indicators suggesting that 1990 would be an ENSO year, the Cane-Zebiak model successfully predicted normal sea surface temperature in the eastern and central equatorial Pacific. Predicting cold (La Niña) conditions as in 1988 has been less successful (Palmer and Anderson, 1993). Moreover, with the exception of the recently implemented coupled ocean-atmosphere GCM at NMC, most models failed to predict the secondary warming in the equatorial Pacific in early 1993 following the 1991-1992 ENSO.

Most progress in climate prediction has come from studies of a small number of warm ENSO events (about 10) and even fewer La Niña events over the past 40 years. Moreover, only in the past 10-15 years have the oceanic data been of sufficient quantity and quality to examine critical ENSO-related processes in detail. Research is now advancing on other interannual and interdecadal time scale phenomena through the analysis of global data sets and the development of coupled models capable of investigating the role of non-ENSO-related oceanic anomalies (e.g., at higher latitudes and at greater depths than observed during ENSO). There is reason to be optimistic that climate forecast models will continue to improve in terms of sophistication, resolution, and accuracy as computer power steadily increases, as our understanding of the physical system deepens, as our observational data bases grow in time and space, and as our ability to assimilate relevant data sets for initialization is refined.

If acted upon, skillful climate forecasts offer a potential to society for mitigating against the negative impacts of climate variability. In the case of ENSO, warm SST anomalies in the equatorial Pacific are associated with a worldwide disruption of weather patterns that affect food production, energy production, land use, transportation, commerce, and recreation (e.g., Glantz, 1984). Well-known examples of ENSO teleconnections (Ropelewski and Halpert, 1986, 1987) include: reduced rainfall or drought in Australia, Indonesia, the Philippines, Southeast Africa, India, and Northeast Brazil; excessive rain in western South America, the central equatorial Pacific, equatorial east Africa, the Gulf Coast states and Great Basin of the U.S.; and unusually warm air temperatures in the Pacific Northwest, northeast North America and Japan. Early warning systems for famine use this information. In the southwest U.S., ENSO can be associated with either extremely wet or extremely dry conditions. Coupled with the occurrence of ENSO events, the frequency and severity of hurricanes tends to be reduced in the Atlantic (Gray et al., 1993), and typhoons in the tropical Pacific tend to occur more frequently east of the date line. Many of the atmospheric global teleconnection patterns associated with the warm phase of ENSO are also manifest during La Niñas, but with opposite sign (Halpert and Ropelewski, 1992). The tendency for a La Niña to occur the year following an ENSO event can exacerbate the adverse impacts of interannual climate variability since, for example, a year of drought may be followed by a year of flooding in certain regions.

Fisheries along the west coast of the Americas can be significantly disrupted when physically-controlled changes in the primary productivity alter the dynamics of the food-chain and the availability of commercially valuable fish stocks. The contribution of ENSO to periodic downturns in the anchovy and sardine fisheries of South America is one example (e.g., Quinn et al., 1978; Barber and Chavez, 1983). Some warm water species migrate poleward along the coast, appearing at subtropical and higher latitude locations. In the Pacific Northwest, salmon experience significant mortality in association with ENSO-related changes in the physical environment (Pearcy and Schoener, 1987); and in the tropical Pacific, the species distribution and catch of tuna are affected by the large-scale ENSO thermal anomalies.

The impact of ENSO events is relatively well known. The next question is, what is the value to society of having advance knowledge of the ENSO event? Can any of the losses be mitigated? Can any of the changes, say in rainfall, be taken advantage of so as to gain a positive benefit from the event? What, in fact, is the socio-economic benefit of a short-term climate forecast?

It has been estimated (O'Brien, 1992) that ENSO forecasts a year in advance with 60% skill could potentially save the agricultural, fisheries, and forestry sectors of the U.S. economy about $0.5-1.1 billion per event, or $183 million per year over a 12-year period, based on a saving of $732 million per event (approximately the mean of the quoted range of event savings). This savings would increase to approximately $300 million per year if the skill of ENSO forecasts improved to 77%, which is realistically achievable.

A quantitative study of agriculture in the southeastern United States (Adams et al., 1994) used actual records of climatic variability to estimate improved crop yields that could have been obtained if only the climatic variability had been known in advance. Econometric models then gave the increased value of the agriculture industry, due to the use of the perfect foreknowledge of climate information. The value of perfect climate predictions was about $265M/year, on average, for just the agriculture sector in just this limited geographical region. Increasing the accuracy of present ENSO forecasts by one-third captures about one-half the perfect information value, or about $130M, thus suggesting the value of increased skill and quantifying how much additional investment is justified. The study is being extended to the entire U.S.A., and the methodology is being extended to the water resources and energy sectors as well.

In Australia, every 0.5°C of ENSO-related cooling of the waters off northern Australia equates to about $1 billion in lost agricultural revenues (Nicholls, 1985a, b). Three-month seasonal outlooks have been issued for three years to advise the agricultural community on planting and harvesting decisions, and on the use of pasture lands. Already, experimental ENSO forecasts form the basis of an economically successful program in Peru (soon to be introduced to Ecuador) that advises farmers on whether to plant rice or cotton (crops with very different water demands). In northeast Brazil, ENSO advisories have guided the planting of corn, rice, and beans with encouraging results since 1988. In Ethiopia, advice based on ENSO forecasts has guided land-use strategy, conservation policies, and economic assistance policies since 1987.

The GCOS Working Group on Socio-Economic Benefits (of climate forecasts for seasonal and longer outlooks) is currently reviewing and summarizing extant work on the value of GCOS. Although it is more straight-forward to estimate benefits for ENSO events, there are also substantial benefits to longer-term climate predictions. Examples are given in Thompson (1976), Phillips et al. (1978), Cowen (1985), and Krasnow (1986). The GCOS Working Group will report its conclusions in September 1994 in Geneva at the WMO Conference on the Economic Benefits of Meteorological and Hydrological Services.

Applications of climate forecast information certainly will increase with time as the skill of the forecasts improves and as the regional impacts of various climate phenomena become better documented and understood. An overview of existing literature (and annotated bibliography) on the socio-economic value of climate forecasts has been prepared by Murphy (1995) for NOAA.

## I.C. Other (Non-climate) uses of Ocean Observations for Climate

The long-term goals for which an ocean observing system for climate are being planned and implemented are to monitor, understand, and predict climate change. However, there will be many other applications of the resulting data with significant societal benefit.

In shelf and coastal waters, the observations of the ocean observing system for climate will provide data products that will form a basis for observations of the coastal module of GOOS and enable regional climate change to be put in a larger perspective. They will also provide a baseline that will enable nations to put in place local observation systems of higher resolution to meet national objectives. Both in coastal and in open-ocean waters, the observing system will contribute to the data needs of the health of the oceans, living resources, and services modules of GOOS.

Surface ocean data from the ocean observing system for climate will be assimilated into NWP models and improve weather forecasts, although the quantification of this benefit is difficult. This will in turn lead to improvements in the estimates of surfaces fluxes of momentum, heat and fresh water provided by the NWP models. When reanalyzed, past NWP predictions will provide uniform surface ocean fields, over a number of years, that are not affected by the changes in the prediction schemes that have been made from time to time to improve weather forecasts.

Thus, the cost and complexity and scale of the proposed observing system for climate need not be justified only by its benefits to climate monitoring, detection, and prediction. These same observations, and many of the resulting products, manifestly will produce many other benefits in the shorter term.

## I.D. Contents of Report

Section II of this report, The Ocean and Climate, gives a brief description of the ocean's role in climate.

The general considerations that guided the OOSDP in formulating an ocean observing system for climate are discussed in Section III, System Design Considerations. This begins with a discussion of key elements in the design strategy. Then, the overall design goal of the OOSDP is repeated and the subgoals of the ocean observing system are stated. Given next is an enumeration of the characteristics expected of the measurements needed for the system to be operationally feasible. The section concludes with a discussion of the stages in design of an observing system and the role of models.

The space and time variability of ocean variables that must be measured or estimated by the observing system are discussed in Section IV. Knowledge of these scales of variability is essential for designing the observing system; many scales are poorly known now, pointing to the need for additional knowledge on the basis of which the system design will evolve.

Then, based on the observing system subgoals of Section III.B and the scales of variability discussed in Section IV, the OOSDP recommendations for measurements to be included in the observing system are given in Section V, Elements of the Ocean Observing System for Climate. The recommended measurements are organized by time of implementation: elements of existing "operational" systems; elements to be added now to form the initial observing system; and elements, perhaps not now readily obtainable, urgently required to enhance the initial system at the earliest feasible time. In addition, selected research and development initiatives are recommended.

The elements and system needed to manage the data acquisition, transfer, quality control, and archiving, as well as the production and distribution of products, are presented and briefly discussed in Section VI, Information Management. Linkages to existing information management systems are discussed further in Annex II.

Section VII, System Organization and Evolution, begins with discussions of enabling research and the technology development which will lead to better scientific understanding and refinement of design criteria, and to improved tools and techniques for implementation and evolution of the observing system. Annex III to this report lists respondents who contributed ideas in response to a questionnaire on enabling technology for the ocean observing system for climate. Then, the requirement is presented for a unit within the observing system, which carries out system self-assessment and strategic planning. This is followed by a discussion of the need to consider alternative sampling strategies. Section VII ends with a suggested management system.

The OOSDP attempts in Section VIII, "System Integration; Synthesis", to summarize and prioritize our recommendations for an ocean observing system for climate. For each subgoal, we assess the impact and feasibility of each observation recommended to achieve this subgoal. The observations recommended as part of an initial observing system to meet the subgoals are summarized. Included also is a summary of all the subgoals to which each recommended observational element contributes. Then, the subgoals are ranked as to priority at this time, and an analysis presented of the additional observations needed to meet each lower ranked subgoal. Finally in Section VIII, the Panel presents its view of additional activities that must be included in the design of a coherent and effective ocean observing system for climate.

Other annexes include the complete terms of reference for the OOSDP and a listing of acronyms used in this report.

# II. THE OCEAN AND CLIMATE

Earth's climate system consists of five major components: the global atmosphere, the world ocean, the cryosphere, the land surface, and the biosphere. All subsystems are coupled, with the complete system exhibiting variations from seconds to millions of years. The ocean shows variations on all of these time scales; the best understood are those of the diurnal and seasonal cycles, where the variations in radiation are known, and the response of the system is strong. Interannual variations of the atmosphere-ocean system are beginning to be understood and experimental predictions have shown some skill. Variations with decadal time scales are just beginning to be documented.

It is useful at the outset to describe what we mean by "climate". For the purposes of this document the climate is a set of low frequency averages of variables of interest, with their associated variances. Thus it is possible to speak, for example, of the "mean climate" or the "mean monthly climatology" of ocean temperature or salinity or currents over a given period of time. All available information suggests that there has been considerable climate variability over recorded history. This variability may be contained primarily in the variances if the averaging period is long, or in the evolution of both the means and the variances if the averaging is done over a decade or two. For certain concerns a long averaging period is useful; for others it is more helpful to look at the climate decade by decade.

Much of the present controversy over climate "change" exists because our awareness of climate variability has increased greatly in recent decades. Nowhere is this more so than in the ocean. Only in the 1970s was the true range of ocean variability comprehended, as it became possible to make long-term high time resolution measurements of the subsurface ocean. A major aspect of the ocean observing system for climate will be to enable the first reliable climatologies (means and variances) of the subsurface ocean to be prepared. This "baseline" climatology is essential if any future work on climate change related to the ocean is to be possible.

Assessment of the climate information obtained over the coming decades will have to consider how both means and variances are changing, in terms of all available information about previous means and variances. The importance of this task and its several aspects must not be underestimated. Efforts to further analyze the historical record and to interpret the new information from the observing system in terms of the historical record will determine much of the effectiveness of the observing system in the next few decades.

We have only a partial understanding of the role of the ocean in the coupled climate system of the Earth. In spite of their widely different time scales, mesoscale ocean eddies, the global effects of an El Niño, deep water formation, and greenhouse gas warming are all manifestations of the complex interactions between the atmosphere, land, and ocean. For the most part they can only be poorly modeled and hence poorly predicted. Although our understanding of ocean climate is increasing through research programs such as those of the WCRP, many aspects require systematic long-term global observations for significant improvements.

A brief description of the ocean's role in climate follows. More detailed information on what is known about the space and time variability of ocean properties and of the measurements needed to resolve this variability is given in Sections IV, V, and VIII.

## II.A. Physical Aspects of the Climate System

Earth's climate system is driven by the radiative energy from the Sun. The ocean absorbs over half the radiation that reaches Earth's surface. As the ocean warms, some heat is mixed downwards and some escapes back to the atmosphere, largely as latent heat of evaporation, but also through long-wave radiation and sensible heat flux. At high latitudes cooling may make surface water heavier so that it sinks and spreads the cooling over considerable depth, sometimes to the ocean bottom. The

Sun's energy also drives the large-scale wind systems and convective cells of the atmosphere. In turn the winds, along with the sinking heavier water masses, drive the large-scale ocean currents which redistribute the energy absorbed from the Sun. Thus, the Gulf Stream and Kuroshio currents carry heat from low latitudes northward where some is lost to the atmosphere. This, for example, greatly moderates the climate of western Europe both making it warmer over a year and with less variability in the seasonal cycle than if the climate resulted from a direct radiative balance with the Sun. The ocean circulation resulting from this distribution of heat and consequent winds is highly turbulent and difficult to characterize or model.

Since incoming solar radiation is greatest at low-latitudes, and since it is known from satellite measurements that Earth radiates energy back to space almost uniformly, the overall radiative balance requires a net transport of heat by the ocean and atmosphere towards the poles. In recent years oceanographers and meteorologists have been able to estimate the portion carried by both the winds in the atmosphere and currents in the ocean (Hall and Bryden, 1982; Carissimo et al., 1985). These individual estimates show that at mid-latitudes the ocean and atmosphere contribute similar amounts to the poleward flux, but that the total heat transport as estimated falls short of the total needed to meet the observed radiation balance by about 40% (Bryden et al., 1991). Whether this represents an inconsistency in the radiation measurements (Gilman and Garrett, 1994) or a problem with the oceanographic or meteorological estimates (Trenberth and Soloman, 1994) remains an important uncertainty in our knowledge of Earth's climate system.

It is at the sea surface that the ocean responds most directly and rapidly to the atmosphere through the air-sea fluxes of heat, mass, and momentum from atmosphere to ocean and vice versa. This is to be seen in the resulting small-scale variability in SST, sea surface salinity (SSS) and near-surface currents with time scales of a day and less (see Section IV.A). However, uncertainties in present estimates of these fluxes are large. Climatologies formed from decades of weather reports from ships have yielded notably different flux estimates (Bunker, 1976; Isemer and Hasse, 1987). This is because of uncertainties in exchange formulae, scarcity and poor quality of the observations, and different philosophies of data treatment. Direct measurements of fluxes over the ocean are now possible locally but are difficult and rarely done. The more common bulk formulae estimates of the fluxes, either based on observations of mean quantities or the output of NWP models, have uncertainties that are large compared to climate-related signals. It is a challenge, for example, to reduce error in the total surface heat flux to less than 10-20 W/m$^2$. The present uncertainties in the surface fluxes integrated over an entire ocean basin lead to large discrepancies in the coupled ocean-atmosphere heat balance and the uncertainty in Earth's heat balance as mentioned above.

Similarly, the ocean exchanges freshwater with the atmosphere via evaporation at the surface and precipitation, both terrestrial and marine. The ocean contains over 97% of the world's water and is the source of most of the water that rains on land (the atmosphere holds only 0.001%). Freshwater fluxes across the surface are not well defined as can be seen from various estimates of the net freshwater loss over the North Atlantic which differ by almost 5 x 10$^5$ m$^3$/s, an amount more than 2.5 times the flow of the Amazon river. In addition, the freshwater flux has a first-order impact on surface buoyancy. Because surface salinity variations have no feedback mechanisms with the atmosphere, they have larger time scales than SST anomalies.

The variations of wind stress over the ocean drive significant ocean currents and hence transports of heat and fresh water between the equator and higher latitudes. Our present knowledge of the wind climate is limited in several aspects. Most observations are of wind velocity. The corresponding wind stress value depends on the roughness of the sea surface; quantifying this relationship remains a subject of research. Although variations in wave climate suggest interdecadal changes in the wind field, detection of these from the available observations is made difficult by changes in observation methods (Cardone et al., 1990; Peterson and Hasse, 1987). Climatologies of wind stress in use by ocean modelers at present show differences greater than 20% in many regions, due both to limited available observations and also the choice of different drag coefficient parameterizations. Wind stress curl differences can be even greater in regions of significant wind stress gradient. Better determination of the wind stress fields is an important priority for the observing system.

In this report we consider sea ice, but not other elements of the cryosphere, in relation to climate. The characteristics of sea ice render it important to global and regional climate. First, sea ice has the characteristic feature of high albedo and plays a role as an insulator restricting sensible and latent heat fluxes between the ocean and atmosphere. Thus, the presence of sea ice causes more cooling of the surrounding atmosphere and leads to further development of ice cover. A positive feedback effect also occurs in the process of ice melting; its onset accelerates the retreat of the ice cover. Therefore, sea ice may be a sensitive indicator for climatic change such as warming due to increased greenhouse gas concentrations.

Second, sea ice can be quite mobile and has characteristic fluctuations in both space and time. In polar regions, sea ice extent and concentration vary on interannual and longer time scales, strongly influencing the regional climate. As an example, the range of seasonal variations in sea ice coverage in the Southern Ocean is comparable with the ice-covered area of Antarctica. Sea-ice cover with its high albedo and good insulation, meridionally advances in winter and retreats in summer. Within the advancing and retreating ice cover, sea ice floes easily move with wind and current.

Third, sea ice redistributes heat and salt. Freezing of sea water and growth of sea ice in high latitudes result both in salt gain to the ocean by brine rejection and latent heat gain to the atmosphere. Brine rejection leads to the production of dense water contributing to the renewal of deep and bottom waters. The advection of the sea ice toward lower latitudes causes both fresh water gain and heat loss by the ocean through ice melting. Model studies indicate that warming from greenhouse gases will appear first in high latitude regions over the continents and that ice extent will be affected. This has not yet been observed but long time series of accurate data are lacking.

Within the ocean, the vertical and horizontal distribution of properties and currents is complex. The upper layer, which in the tropics is the order of 10 to 100 m thick, has major variations on interannual and shorter time scales. Below the upper layer is a permanent thermocline (reaching to about 1000 m), a region where the salinity and temperature rapidly approach their deep water values. In spite of its importance in the climate system and as the home of most of the ecosystems, the upper layer of the ocean is poorly observed on a systematic basis, particularly in the Southern Hemisphere and at high latitudes in both hemispheres.

The upper ocean, especially the mixed layer, is strongly influenced by the atmosphere. Because the heat capacity of the top few meters of the ocean is roughly equal to that of the atmosphere over it, the ocean contains the longer term "memory" of the climate system. Climate affects on time scales of months to years primarily involve the upper ocean. Over much of the ocean, especially at high latitudes, the strongest signal in the upper ocean arises from the seasonal changes in radiative and wind forcing. However, the strongest oceanic effect on climate on seasonal to interannual time scales arises from ocean-atmosphere interaction in the tropical Pacific, the well-known ENSO phenomenon (Philander, 1990). El Niño, which is the oceanographic manifestation of ENSO, is characterized by the appearance of warm surface waters in the eastern and central Pacific at irregular intervals of approximately two to seven years. Dynamically linked to El Niño is the Southern Oscillation, a large-scale oscillation of surface air pressure between the tropical Indian and Pacific Ocean. These east-west variations in air pressure are associated with changes in the strength of the tradewinds, which in turn affect the circulation of the upper ocean through the excitation and propagation of planetary scale equatorial waves. ENSO events typically last about 12-18 months (Rasmusson and Carpenter, 1982), although there are significant event-to-event differences in the details of their evolution (cf. Cane, 1983; Kousky and Leetmaa, 1989; McPhaden, 1993).

El Niño is initiated when the tradewinds weaken in the central and western Pacific, generating baroclinic Kelvin waves which depress the thermocline in the eastern Pacific; and baroclinic Rossby waves which elevate the thermocline in the western Pacific (McCreary, 1976). This redistribution of upper ocean mass leads to anomalous warming of sea surface temperatures in the equatorial cold tongue by reducing the efficiency of equatorial upwelling in cooling the surface. Enhanced atmospheric deep convection over the anomalously warm SSTs reinforces weakening of the tradewinds in the central and western Pacific, resulting in a positive feedback that leads to instability of the coupled ocean-atmosphere system. The duration of ENSO events is set by the growth rate for this coupled instability, combined with the time it takes for equatorial Kelvin and Rossby waves to cross the basin. According to the "delayed oscillator theory" (Schopf and Suarez, 1988; Battisti, 1988), the termination of ENSO events is brought about by reflection at the western boundary of Rossby waves generated by the initial collapse of the tradewinds. The reflection process generates upwelling equatorial Kelvin waves, which propagate into the eastern Pacific where they erode the warm SST anomalies by elevating the thermocline to enhance the effects of vertical mixing. The prediction of ENSO events is discussed in Sections I.B.3 and I.B.4.

The global ocean circulation can be characterized as a turbulent system including major gyres that circulate water within basins; the Antarctic Circumpolar Current that links the waters of the South Pacific, South Atlantic, and South Indian Oceans; and interbasin fluxes through such regions as Indonesia between the Pacific and Indian Ocean. These are essentially wind-driven phenomena to which must be added the overturning or thermohaline circulation forced by the sinking of cooled surface waters, primarily around Antarctica and in the northern North Atlantic. In general, we know more about the magnitude of this large scale circulation than its variability. However, even the former is not adequately documented over the globe although its description will be improved with the completion of WOCE. The "mean" circulation takes place in an ocean filled with mesoscale eddies (the "ocean weather"), whose kinetic energy is often one or two orders of magnitude greater than that of the mean flow and whose horizontal scale varies from a few hundred kilometers at mid-latitudes to tens of kilometers in weakly stratified polar regions. The distribution of eddy energy, to the extent that it can be defined by the sea-surface topographic expression of the eddies, has been mapped by satellite altimeters. Figure II.A-1 shows rms height variability over the world ocean as observed by TOPEX/POSEIDON.

The major ocean currents redistribute heat, fresh water, and other properties. Zonal hydrographic sections taken across ocean basins have been used to estimate the net transport of heat and fresh water through the section. Using sections at 24°N in the Atlantic and Pacific, Bryden et al. (1991) have estimated the global northward oceanic heat flux at this latitude to be about 2 petawatts. WOCE is providing a number of such high-quality sections globally that will allow strong basin-averaged constraints to be placed on surface heat and water transports inferred from the atmospheric and radiative measurements. The importance of such measurements is illustrated by the fact that until recently it was far from clear how surface flux estimates of fresh water could be integrated to form a coherent picture of global oceanic transport (Wijffels et al., 1992). This means that the most popular conception of the mean oceanic water budget was in error by an order of magnitude in the treatment of Pacific to Atlantic throughflow (see Section IV.E).

In selected areas of the ocean, there is rather direct communication between surface and deep waters. In some open ocean areas relatively high near-surface salinity and weak vertical stratification create conditions such that cooling winds regularly cause deep convection to the bottom or great depth; principal examples are the high latitudes of the Atlantic, the Arctic Basin, and the Mediterranean Sea. In other areas, notably around Antarctica, cold shelf water mixes at the shelf edge with relatively salty near-surface waters to form waters that sink to great depth or the

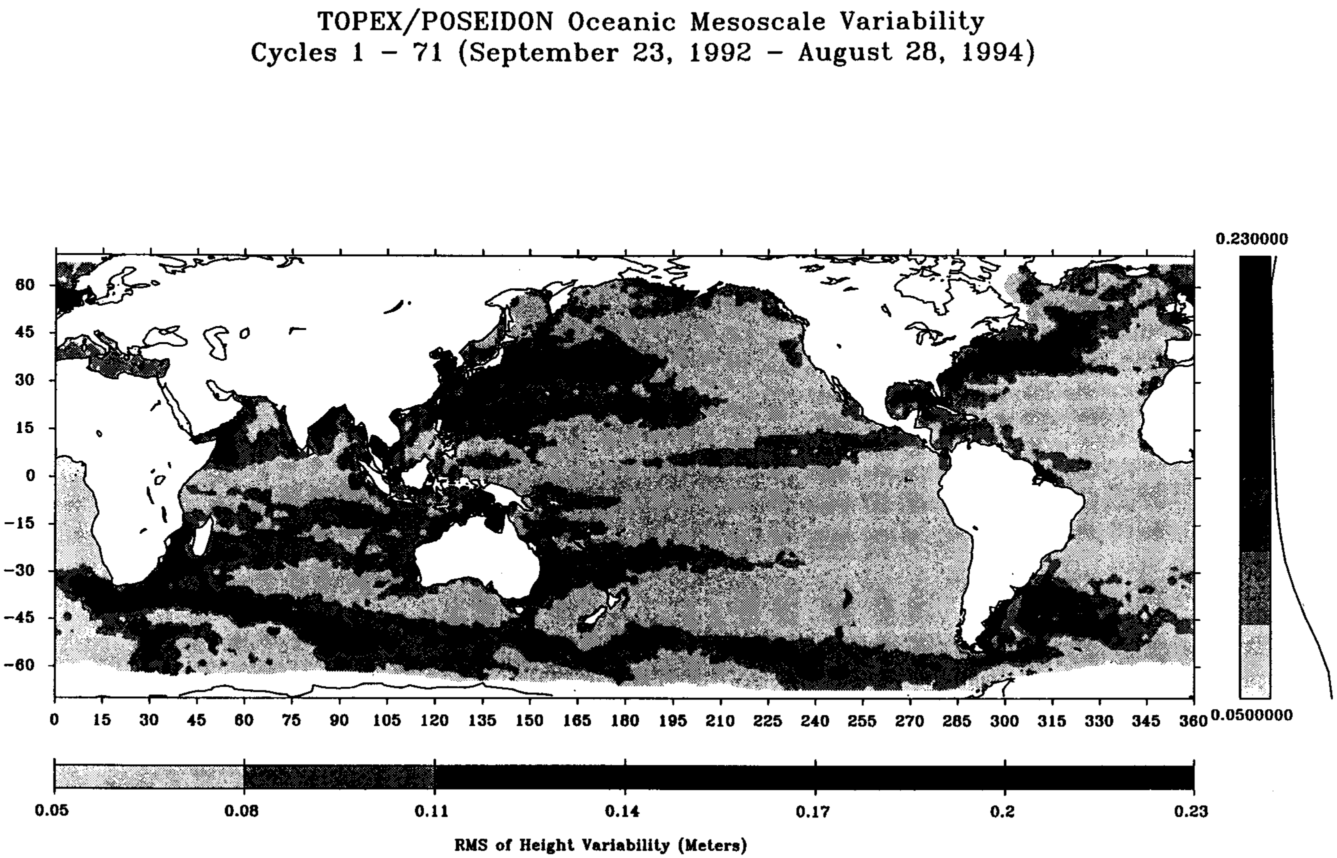



Figure II.A-1. The ocean mesoscale height variability observed by TOPEX/POSEIDON during September 1992 - August 1994 (cycles 1 - 71). The height variability is the geographically-smoothed standard deviation of the height values at points along the satellite's ground track. The variability was smoothed using a radially-symmetric, Gaussian weighting function. The normalized histogram next to the gray bar scale for height variability shows the data distribution of height variability. Tides have been removed from all deep water areas. However, the large variability in shallow coastal regions, e.g., the Gulf of Carpentaria and the Yellow Sea, still includes some tidal signal. The figure clearly shows the height variability associated with the main ocean currents, e.g., the Gulf Stream, Kuroshio, and Antarctic Circumpolar Current. (Figure provided by Tapley.)

bottom. Deep, cold, boundary-intensified flows and oceanic upwelling complete the return flow. Heat, water, and a variety of chemicals are carried around by the circulation. There is strong evidence in the geological record that the areas and rates of deep convection were strongly modified by surface freshwater inputs. That is, the lowering of upper ocean salinities increased the stratification so that the heat content of the deep ocean could not be released to the atmosphere. Massive changes to ocean circulation may have occurred during the Younger Dryas event 11,000 years ago when glacial melt water prevented deep convection in the high latitude North Atlantic, plunging northern Europe back into glacial conditions (Broecker et al., 1985). Similar changes in the formation of deep water have also been found to operate on decadal time scales (Dickson et al. 1988). It appears from model studies that deep convection, especially around Antarctica, will inhibit greenhouse gas warming of the atmosphere both locally and globally. The thermohaline ocean circulation also directly impacts global biogeochemical cycles including the oceanic uptake of carbon dioxide.

Deterministic predictions of climate changes involving the deep ocean are not yet possible (see also Section I.B.3). The reason lies in our lack of understanding of the full-depth global ocean and the extent to which it is feasible to define an initial state of an ocean that has many attributes of a chaotic system. However, global observations and the development of a variety of ocean models are rapidly improving our ability to describe the ocean and its physics. This has lead to some confidence that the ocean's role in delaying greenhouse gas warming and the resulting changes in sea level are being increasingly well represented by coupled ocean/atmosphere models.

## II.B. Biogeochemical Aspects of the Climate System

The ocean contains 60 times more carbon than the atmosphere and is potentially a major sink for anthropogenic atmospheric $CO_2$ (Figure II.B-1). Furthermore, small changes in oceanic circulation can have a huge impact on the concentrations of this trace gas. Atmospheric $CO_2$ that enters the ocean can be transported to depth by a variety of physical and biogeochemical processes. Once under the main thermocline, $CO_2$ is effectively removed from atmosphere-ocean exchanges for time scales of decades to centuries.

Atmospheric $CO_2$ enters the ocean by gas exchange controlled by the wind speed and the difference in partial pressure between the atmosphere and the ocean. The concentration of dissolved $CO_2$ at the surface is a function of temperature through its effect on solubility. Solubility increases as temperatures fall so that cold surface waters pick up more $CO_2$ than warm waters. $CO_2$ enters the ocean at high latitudes and outgasses to the atmosphere at low latitudes. Thus, the direction of meridional transport of $CO_2$ by the oceans should be opposite to that of heat, with the transport of both reaching maxima at mid-latitudes.

Physical transport of $CO_2$ to the deep ocean is achieved by the thermohaline circulation. Some of the $CO_2$ absorbed at high latitudes sinks to depth in zones of deep water formation. Thermocline ventilation at mid to high latitudes also transports a substantial fraction of the surface $CO_2$ into the ocean interior. As atmospheric $CO_2$ increases, the gradient in partial pressure between atmosphere and ocean also increases, resulting in higher invasion of atmospheric $CO_2$ in high to mid-latitude waters. Conversely, in outgassing areas, the air-sea gradient is smaller, and outgassing is reduced. The result is a net uptake of anthropogenic $CO_2$ in the ocean interior (the physical pump). Any effect of climate change on the nature and intensity of physical oceanic transports could have a strong impact on atmospheric $CO_2$.

$CO_2$ is also transported to depth by the biological pump. Photosynthetic microorganisms in the surface layer incorporate inorganic carbon into their tissues, resulting in a decrease in the partial pressure of $CO_2$ in surface waters. Much of this organic carbon is returned to $CO_2$ in the surface layer through respiration. However, a significant fraction settles below the main thermocline and is remineralized to $CO_2$ in the ocean interior. It is this imbalance between photosynthetic utilization of

$CO_2$ and remineralization that constitutes the biological pump. This biological transport leads to a vertical gradient of increasing $CO_2$ between the surface ocean and the deeper ocean.

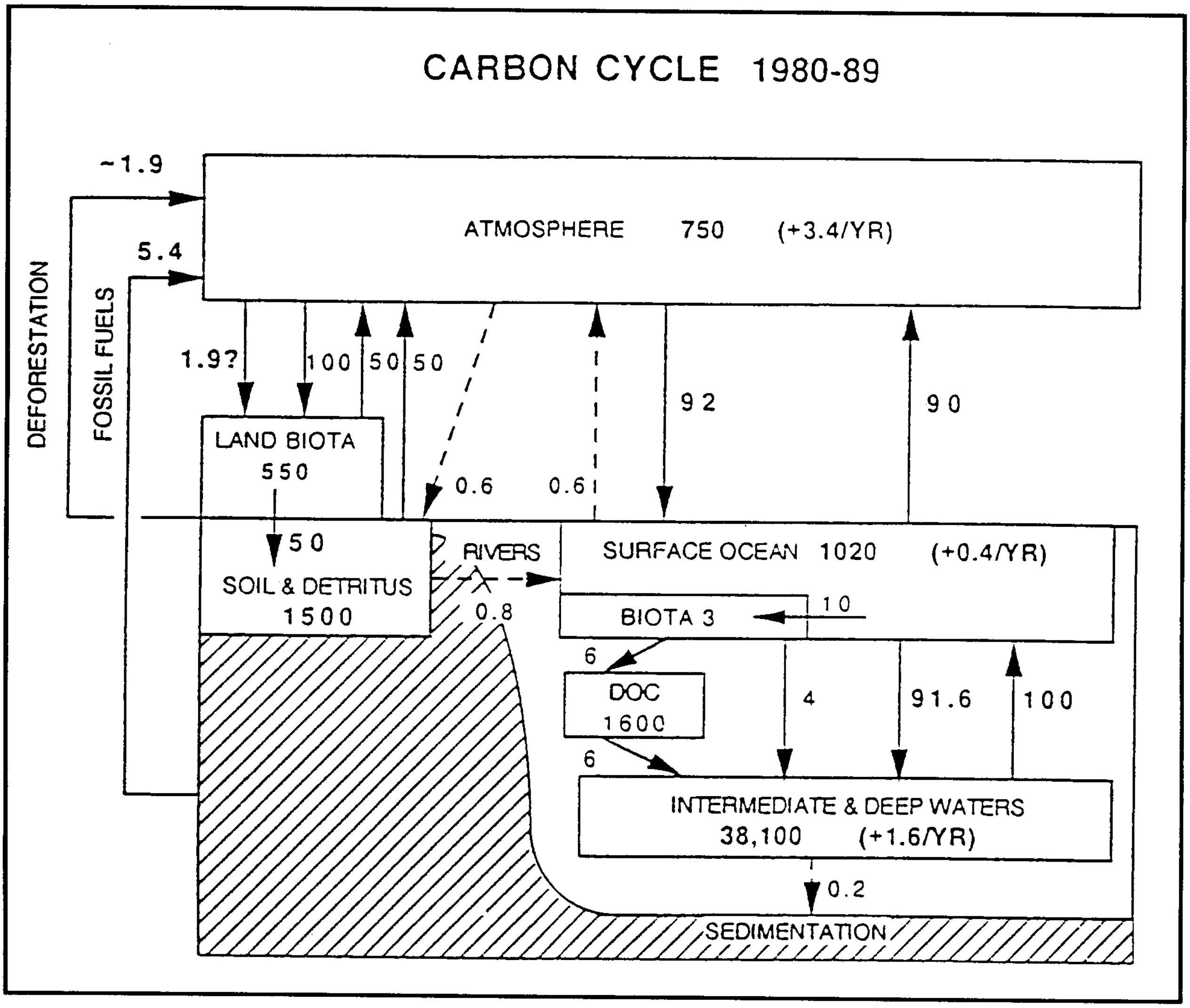



Figure II.B-1. The global carbon cycle reservoir and fluxes (from Siegenthaler and Sarmiento, 1993, in Wallace, 1995). Reservoir sizes are given in gigatons of carbon (Gt = $10^{15}$g). Fluxes and rates of change of reservoirs [shown in ( )] are given in GtC/yr.

On a global scale, according to the most recent ocean carbon cycle models, the downward transport of $CO_2$ by the physical and biological pumps amounts to 102 Gt C/yr and the upward physical transport amounts to 100 Gt C/yr, leaving a net uptake of approximately 2 Gt C/yr (Siegenthaler and Sarmiento, 1993). The biological pump is limited by a variety of physical and chemical factors, but not by $CO_2$. However, climate change could affect these limiting factors. For example, photosynthetic production is dependent on seasonal variations of the mixed layer depth. Climate change could affect the annual cycle of mixed-layer depth and in turn the importance of the biological pump. On a global scale, these physical processes and others (e.g., upwelling), through their effect on the biological component, could alter the balance between downward and upward carbon fluxes in the ocean and affect atmospheric $CO_2$ concentration on climate scales.

In summary, carbon cycling on the global scale is strongly influenced by the wind, temperature, mixed layer dynamics, biological processes and ocean circulation. However, the spatial scale and magnitude of these processes cannot be quantified nor can temporal change be defined with our present knowledge. It is however reasonable to propose the basis of a global sampling strategy which can be improved as the results of the detailed regional process studies within JGOFS become available.

The biogeochemical sulfur cycle may also have an effect on climate change. In the oceans, dimethyl sulfide is produced by senescent microalgae, zooplankton grazing and bacterial degradation (Matrai and Keller, 1993; Dacey and Wakeham, 1986). Over oceanic basins and remote areas, atmospheric sulfate is derived mostly from the oxidation of dimethyl sulfide into sulfur dioxide ($SO_2$), sulfate ($SO_4^{2-}$) and methane-sulfonate (Falkowski et al., 1992). However, we still need much greater understanding (both qualitative and quantitative) of the processes that influence the marine biogeochemical cycle of sulfur in seawater, to predict how perturbations, such as global warming or increase in ultraviolet light, will influence dimethyl sulfide emission to the atmosphere (Malin et al., 1992).

Both the direct scattering of short-wavelength solar radiation and the modification of the shortwave reflective properties of clouds by sulfate aerosol particles increase planetary albedo, thereby exerting a cooling influence on the planet (Charlson et al., 1992). Recent calculations of the effects of both natural and anthropogenic tropospheric sulfate aerosols indicate that the aerosol climate forcing is sufficiently large in a number of regions of the Northern Hemisphere to significantly reduce the positive forcing from increased greenhouse gases (Kiehl and Briegleb, 1993). Systematic global monitoring and regional process studies will better characterize the importance of atmospheric sulfates and improve the accuracy of global climate models.

## III. SYSTEM DESIGN CONSIDERATIONS

This section outlines some of the general considerations that guided the OOSDP in formulating the conceptual design of an ocean observing system for climate presented in this report. As elaborated below, an observing system must support the continuation and/or enhancement of some systems now in place, at least regionally, in support of operational applications and of the programs of the WCRP and the IGBP. These use existing and proven measurement systems. However, all elements of a well-designed observing system may be subject to change with the development of new technology or increased understanding of the nature of the problem being addressed. An observing system must anticipate and encourage the development of these new technologies to increase its cost effectiveness and to enable observations not possible today. Given our present status of knowledge of the oceans and their role in climate, and our present technological capabilities, the design of many elements must await better understanding of the problems being addressed. Section III.A ends by describing the time-phased approach we recommend for system implementation.

The measurements obtained from an observing system can be combined in many ways, serve many purposes, and meet different requirements. Because this diversity makes specific recommendations difficult, especially where priorities need to be set, the OOSDP chose to apply their terms of reference in the setting of a number of goals and subgoals chosen to define specific aspects of climate variability and its prediction as outlined in the previous two sections of this report. The success of the design of the observing system given here can in large measure be evaluated by its ability to meet these subgoals which are presented in Section III.B.

If the measurements specified for the observing system, and the products produced, are to be operationally feasible, practical and cost-effective, they must have certain characteristics. Such attributes have been discussed broadly within the ocean science community during the past five years. Generally accepted necessary characteristics are listed in Section III.C.

Finally, it is useful to present some general considerations on the methodology of observing system design before embarking on a detailed discussion by elements. In Section III.D we suggest the stages through which the development and application of an operational ocean sampling design likely will progress and discuss in general terms the role of models in the design and operation of the observing system.

### III.A. System Design Strategy

Our existing understanding of the ocean is almost completely based on information obtained through the years from a variety of research programs, usually in restricted areas. To this base have been added global climate research programs (e.g., the WCRP's TOGA, WOCE, GEWEX, and Arctic Climate System Study (ACSYS) and the IGBP's JGOFS). Many observational elements of these programs are included in the observing system described in this document, and if continued could provide a head start on the ocean observing system for climate. Thus, it is critical that continuity between these research programs and the observing system be achieved. The study of long term phenomena requires continuity of the data series and its quality even when one changes methods of estimation. Long-term ocean measurements are rare regionally, and nonexistent globally.

Models are an essential element of an observing system. They are required for the assimilation and interpretation of the data, for network design, and for quality control. The models available or being developed at this time, mostly as a result of research programs, are not adequate to meet many of the requirements of the observing system and the development of models and assimilation procedures is essential. The future combination of models and data from the observing system will provide information, which will lead to improved system design and improved products for users.

Thus, the development of models and the establishment of analysis centers must be considered an integral part of the observing system.

New technology will be another key component of the observing system. Indeed, part of the motivation for the present planning process is the greatly enhanced monitoring capability promised by a new generation of lower-cost and longer-lived ocean instrumentation. Low-power computers and sensors are engendering novel instrumentation, which, when combined with the promise of global data transmission capabilities, could make the recommended observing system a practical reality in the next decades. At this time, it is important that sponsoring agencies begin to make investments in research and development required to bring about the most cost effective solutions to the instrumentation and data telemetry problems faced in developing the observing system. For the long term, mechanisms must be set up to assure that new technological approaches are continuously developed, evaluated, and incorporated into the operational system.

It is important to remember the OOSDP is charged with designing an ocean observing system for climate with two purposes: 1) "to monitor, describe and understand the physical and biogeochemical processes that determine ocean circulation and the effects of the ocean on seasonal to decadal climate changes" and 2) "to provide the observations needed for climate predictions". Since the ability to define the observations required for climate prediction depends on the degree of understanding of the climate system, it is clear that the design of an observing system to meet the second charge to the OOSDP will evolve with the success of the first as well as depend on the information produced by current global ocean research programs.

The observing system must deal with a continuum of oceanic space and time scales. For design purposes, especially concerning observations for climate change prediction, the Panel has found it useful to separate the requirements for observations on time scales of months to years (WCRP Stream 2, for example ENSO events) from observations on time scales of years to decades (WCRP Stream 3). This is reflected in the subgoals given in the next section.

To meet the subgoals, the Panel has considered the measurements necessary to define a number of components of the ocean climate system, including the heat, fresh water and carbon balances. These balances depend on oceanic storage, internal transport, and air-sea fluxes. It is possible to estimate for these quantities the accuracy at which each needs to be determined, thus leading to an observational strategy for its measurement. Similarly, the Panel has addressed measures of the ocean circulation including water mass conversion, mass transport, and velocity.

An ocean observation system that included all the observational elements determined by consideration of separate components of the ocean climate system would, in general, contain redundant elements. Some ocean components can be observed with different techniques, some observations or suites of observations can measure more than one component, and some components can be determined from the observation of others, usually through the use of models. For example, the net change in the storage of a quantity is equal to the imbalance of the fluxes in and out of the region of interest. Models can also provide dynamical constraints that reduce the number of observations required. Initially, our ignorance of many of the mechanisms of the ocean climate system, and the inadequacies of our measurement techniques, are such that a degree of redundancy will be necessary. In the longer term, reduced redundancy will be achieved by strategic tradeoffs.

In designing the system, the Panel has realized that strategic tradeoffs must depend on the existing technology and its cost, scientific understanding of the ocean climate system, and the purposes for the observing system. These will all change with time, partly as an effect of the information obtained from the observing system itself. The Panel has recognized that the observing system must be structured so that it will re-examine these tradeoffs on a continuing basis to take advantage of evolving knowledge, technology, and applications of the data. The observing system must include a component, or components, which examine the ongoing system. Resources must be provided for the critical functions of: 1) monitoring performance of the observing system, 2) defining and evaluating research and technical developments needed for improvement, and 3) re-examining strategic tradeoffs.

The OOSDP recommends a time-phased approach to implementation of the observing system.

1. First, in the light of current climate knowledge, specify the elements of the ocean observing system that should be put in place at the earliest time, and specifically:

   a) identify the elements that are part of existing operational systems;

   b) identify elements to be added now to constitute the initial observing system—either enhancements to existing operational systems or parts of existing research observing systems ready for conversion to operational status; and

   c) identify and specify the observations not now readily obtainable that are urgently required and should be added as enhancements to the initial system at the earliest feasible time.

2. Second, identify future research and development likely to lead to additional operational requirements and additions to the operational system.

The combination of observational elements included as 1a and 1b comprise the initial observing system of the common module of GOOS and GCOS.

## III.B. Goals and Subgoals of the Ocean Observing System for Climate

Considering the many aspects of the ocean's role in climate and the existing and potential applications of a system of ocean observations for climate it is clear that the system must serve many different purposes. The overall long-term goal of the system described in this report is encapsulated in the terms of reference of the OOSDP:

> "to monitor, describe and understand the physical and biogeochemical processes that determine ocean circulation and the effects of the ocean on seasonal to decadal climate change, and to provide the observations necessary for climate predictions".

To help focus the design of the observing system it is useful to set a number of subgoals which relate to the various aspects of the ocean and its role in climate. These subgoals also can be used to provide a systematic means for prioritizing observational elements and assessing the projected outcomes of the system design (Section VIII).

The choice of a particular set of subgoals that will meet the overall goal of the observing system is of course far from unique. However, in selecting subgoals the Panel attempted to address the key issues regarding monitoring, detecting, understanding, and predicting climate variability as discussed in Section I. It should also be emphasized that these choices were made because they are appropriate now, but, since the observing system must be an evolving system, the goals and emphasis adopted now might be less appropriate in the future.

## III. SYSTEM DESIGN CONSIDERATIONS

1. Exchanges between the ocean and atmosphere are critical for the ocean and for the ocean's role in climate. Almost all the information that determines the ocean's circulation is communicated through the air-sea interface, so the determination of surface fields and surface fluxes must be a central goal of an observing system. Because sea ice forms a barrier between the ocean and atmosphere in polar regions, measures of its extent and character also are essential. It must be recognized that the determination of ocean surface fields and fluxes are not solely the concern of an observing system because observations at the ocean surface are required for daily weather prediction and understanding the atmosphere's role in climate. The subgoals of the observing system at the ocean's surface are:

   a) To provide in situ measurements of SST that, when combined with satellite measurements, are adequate for defining SST field variability on monthly, seasonal, interannual and longer time scales. Where it can be determined with sufficient accuracy, sea surface salinity and its variability should be measured.

   b) To assist in providing data at the sea surface and in the marine boundary layer needed to estimate global distributions of the surface flux of momentum (wind stress) on monthly, seasonal, interannual and decadal time scales.

   c) To assist in providing data at the sea surface and in the marine boundary layer needed to estimate global distributions of the surface fluxes of heat and fresh water on monthly, seasonal, interannual, and decadal time scales. Additional constraints on these estimates will be provided by estimates from upper ocean budgets.

   d) To provide the physical, chemical and biological data required to describe the global distribution of sources and sinks for atmospheric carbon dioxide and the carbon exchanges within the interior of the ocean. Initially, monthly climatologies of the exchanges are required to resolve longer term changes in the presence of strong variability on interannual and shorter time scales.

   e) To provide data to describe the extent, concentration, volume, and motion of sea ice on monthly and longer time scales.

The design of an ocean observing system for climate to meet these subgoals must be adequate to enable the detection of natural and anthropogenic climate change on longer time scales in the presence of strong variability that exists on shorter time scales. Determination of various ocean surface properties and fluxes are fundamental to most climate issues.

2. The ocean is generally characterized by seasonally varying surface waters separated from more nearly constant deep waters by relatively large verticle changes in temperature, salinity and density. The surface waters are continually mixed by wind and buoyancy forcing. The upper ocean is a buffer to the exchange of heat and other properties between the atmosphere and deep ocean. It is this buffering action which provides the first level "memory" of the ocean since the total storage capacity of the waters above the thermocline is generally several orders of magnitude greater than the heat stored in the atmosphere. Measuring this upper ocean storage is critical for the deterministic prediction of the variability of the coupled ocean-atmosphere system on seasonal to interannual time scales and for the regular monitoring of climate variability at monthly to interannual scales. The specific subgoals for the observing system are:

   a) To provide global data for monitoring, understanding, and analyzing monthly to interannual upper ocean temperature and salinity variations.

   b) To provide upper ocean data in the tropical Pacific for the initialization and verification of models for ENSO prediction.

c) To provide upper ocean data outside the tropical Pacific for the understanding and description of ocean variability and for the initialization and development of present and future models aimed at climate prediction on seasonal to interannual time scales.

Emphasis has been given to tropical Pacific measurements for ENSO prediction because of its proven feasibility. However, there also are a number of established measurement systems with applications for monitoring and understanding the ocean's role in climate outside the tropical Pacific. Future research and experience will undoubtedly see many of these measurements being utilized for routine model initialization and prediction.

3. In contrast to the buffering and relatively rapid response times that characterize the upper ocean, the deep ocean is characterized by its capacity to sequester heat, fresh water and chemicals from the surface layers and delay exchange for long periods (from decades to centuries). It is this capacity that makes measurements of the deep ocean essential for monitoring and understanding natural and anthropogenic ocean climate variability at long time scales. The focus here is mostly on monitoring, understanding and validation of model simulations rather than model initialization and prediction. The specific subgoals are:

   a) To provide data to determine the changes in oceanic inventories of heat, fresh water, and carbon on large space and long time scales.

   b) To describe changes in the large-scale ocean circulation and its transport of heat, fresh water, and carbon on long time scales through the collection of data and their assimilation in models.

   c) To provide measurements of the long-term change in sea level due to climate change; in particular that arising from greenhouse gas warming.

4. In addition to the subgoals specifically aimed at gathering information over a variety of time scales, the observing system must also focus on providing the infrastructure and techniques, which will ensure that this information is utilized in an efficient way. This synthesis will be achieved in a variety of ways including routine monitoring and analysis (typically at monthly intervals), improved climatologies, and through model data assimilation. The specific subgoals are:

   a) To provide improved global climatologies (means and variances) of key ocean variables such as temperature, salinity, velocity and carbon, especially for the purpose of validating probabilistic climate modeling and simulations at decadal and longer time scales.

   b) To provide the data management and communication facilities necessary for routine monitoring, analysis, and prediction of the ocean from monthly to long time scales.

   c) To develop the facilities for processing assembled data sets and providing timely analyses, model interpretations, and model forecasts.

The effectiveness of the observing system in meeting these subgoals will have direct consequences for the specification of the observing system for the previous subgoals. A more effective methodology for interpolating, extrapolating and drawing inferences from a measurement system will usually imply a reduced reliance on any one particular observation. Ultimately this synthesis will be performed by ocean general circulation model data assimilation systems which will combine all information from the surface, upper ocean and deep ocean to produce a multi-variate description of the global ocean circulation. This system does not yet exist, so, in the meantime, we will rely on a variety of simpler tools.

## III.C. Characteristics of Observing System Measurements

The general approach to the ocean climate observing system design developed in this document demands that the measurements meet certain criteria (e.g., that they should be included as part of the observing system only if it is believed that they are needed long term). During the past four years, such criteria have been discussed in many fora. The ocean community has expressed broad recognition that the observations required to be delivered by the observing system should satisfy the following conditions:

- Long term
  Measurements, once begun, should continue into the foreseeable future. Continuity in the observed quantity is sought, rather than in the method; and it is anticipated that more effective methods will become available with time.

- Systematic
  Measurements should be made in a rational fashion, with spatial and temporal sampling tuned to address the issues of climate variability and change. Further, measurements should be made with the precision, accuracy, and care in calibration required to provide continuity in the quality of data in space and time even though different methodology may be used.

- Relevant to the global climate system
  Measurements should be made either to document the role of the ocean in the climate system or to provide data needed to initialize and validate models that describe and predict seasonal to decadal climate change.

- Subject to continuing examination
  Trade-offs must be subjected to scientific evaluation on a continuing basis to take advantage of new knowledge and technology.

Because of the global scope and intended longevity of the observing system it is realized that there are further practical constraints on the measurements. They should be :

- Cost effective
  Repeat observations are required at many locations. To maximize the return possible using the available resources (financial and manpower), efforts should be made to use observational methods in the observing system that are economical and efficient.

- Timely
  Timely delivery of resulting data is required. In some cases this means in real time, while in others substantial quality control will require lapsed time between measurement and data delivery. In all cases data must be delivered to deadlines.

- Routine
  The observation tasks should be carried out by dedicated staff, responsible for

**Ocean Observing System Measurements**

- Long Term
- Systematic
- Relevant to the Global Climate System
- Subject to Continuing Examination
- Cost Effective
- Timely
- Routine

acquisition and quality control of data and the dissemination of products. Thus for some variables, the collection of observations and related work may be integrated into agencies capable of making a long-term commitment; for other variables, the desired quality of routine observations may be best achieved by providing long-term support to research organizations capable of ensuring the quality and continuity of the measurements. This may vary from nation to nation.

## III.D. Models and Observing System Design

Steps in the design process. Ideally, the scientific development and application of an operational ocean sampling design should progress through several stages.

Stage 1. The beginning usually takes the form of several ad hoc opportunistic analyses of extant information, some of which enable identification, better understanding and more significant appreciation of the key oceanographic processes.

Stage 2. This may be followed by more focused, regional research into the fundamental dynamics and physics of the important processes. This stage of research and obtaining fundamental understanding is a prerequisite and permanent requirement for the development and implementation of operational observing systems. For some aspects of the ocean climate system this research is only now being undertaken or is being planned.

Stage 3. The next stage involves detailed statistical studies of target fields for regions and periods in which, based on the accrued scientific knowledge, it is reasonable to assume the field or fields are being over-sampled. That is, there are more than enough direct observations to estimate the true field and its statistics without recourse to indirect inference, extrapolation or interpolation. Such analyses yield information on the spatial and temporal variability of the field, information that is vital for the observing system design.

Stage 4. To proceed with the design of a regional, basin-scale, or global sampling network there must be faith in the ability of the statistical results of the previous stage to represent the actual ocean variability over the broader domain and for all time periods. If this is so, then there are various methods which will allow the evaluation of particular spatial and temporal sampling patterns in terms of the accuracy with which they can estimate the target field. Such methods have been widely used in meteorology and were employed for the Mid-Ocean Dynamics Experiment, in the design of the TOGA and WOCE Volunteer Observing Ship (VOS) programs and in the design of the TOGA TAO array, to mention just a few oceanographic examples. In essence such methods tell us, for an ocean that obeys our statistical assumptions, how often and how densely we must sample in order to be able to estimate say, the monthly-averaged depth of the 20°C isotherm over a 2° by 5° area to an accuracy of 4 m.

Stage 5. The next stage involves the routine analysis of data from an actual experimental network subject to the typical logistical and technical problems which distinguish it from the ideal world. This analysis may be within a research program, as was the case for upper ocean data in TOGA, or within an existing operational system. The network design must be tested to find out whether it can deliver the theorized product. If it does then there is at least a scientific argument for supporting continuation of the network, perhaps as part of an operational system.

Stage 6. The design and testing discussed above is usually based on the premise that the analysis must be largely formed from local data (in both space and time), and no use is made of information from other fields. There may be some use of historical information or limited spatial extrapolation but the design will not usually depend on sophisticated transfer of remote information by a model. The final stage then is to use models to bring recent information forward to the current period (a forecast/first-guess based on old data) and to extrapolate and draw inferences from observations remote from the analysis site and, perhaps, from a variety of fields, and combine this information with that used for Stage 5. This methodology is commonly referred to as data assimilation or data inversion.

These stages may overlap in some circumstances, or particular stages may receive greater emphasis than others. The stages may not proceed strictly in sequence; on the basis of experience and improved understanding in the later stages it may be desirable to refocus on earlier stages, perhaps even returning to re-examine the fundamentals of Stage 1.

For the complicated, multi-variate processing envisaged in Stage 6, it is extremely difficult to quantify the influence of separate elements of the observation network since data assimilation into a model provides a complex interaction between all elements. There are few model data assimilation systems operating in oceanography and those that do exist have relatively short histories. For the design of an ocean observing system, data assimilation provides the promise of extracting far greater information from the observation data base and, in particular, enables past information to be extrapolated to the target period. The immediate benefits are less reliance on data from the present period and location (and thus less stringent design criteria) and improved analyses/initial conditions on which to base predictions. The potential drawbacks are that the models have errors, sometimes large and poorly understood, and that the oceans are forced by surface boundary conditions (surface fluxes) which are also subject to uncertainty. At this point no ocean climate model data assimilation system has proven skill and we must rely for the most part on studies as described in Stages 4 and 5 for design guidance. In the future, tests using an actual operating data assimilation system should be feasible.

It is important to recognize from the outset that progress in the design is not even. This inevitably impacts on our ability to isolate the important scales of variability for climate (as in Section IV) and to progress from there toward a systematic observing system design.

The role of models. At the most fundamental level, models can be viewed as processors of information. Models by themselves do not provide any new information other than that embedded in the physical and biogeochemical equations and in various parameterizations. For the observing system models will process information in the form of raw instrument output or variable estimates (Level I or II data; see Section VI), combine it with previously processed data (e.g., a forecast or climatology) and output estimates of the fields, usually on a regular space-time grid. Models are tools for interpolation, extrapolation, and inference of observing system information. For many existing ocean model simulations the primary source of information is in the surface boundary conditions. For ENSO forecast models there may be additional subsurface information and a forecast based on prior data. In other cases, the model may be statistical and represent an interpolation of unevenly distributed samples to a regular space-time grid.

The method for combining data and models can be illustrated using a simple example of analysis (Bennett, personal communication); texts such as Bennett (1992) provide detailed discussions of these techniques. Consider the problem of estimating, say, the temperature field $\theta$ at 500 m given a data vector $\mathbf{d}$ of measurements spread in space and time. The standard procedure of objective analysis (Gauss-Markov smoothing) requires a prior estimate of the temperature field $\mathbf{p}$ and an estimate of its error covariance $\mathbf{P}$. These may be from archived data, scale analysis, or intuition. Also assume both the data $\mathbf{d}$ and the prior estimate $\mathbf{p}$ are unbiased estimates of the target field $\theta$, and that the data error covariance $\mathbf{D}$ is known. Note that $\mathbf{D}$ and $\mathbf{P}$ are in essence parameterizations of prior experience in regard to the true field.

An optimal linear estimate for $\theta$ is

$$\theta^a = \mathbf{p} + \mathbf{W}\,(\mathbf{d} - \mathbf{p})$$

where $\mathbf{W}$ is an array of weights chosen to minimize the estimated error variance of this analysis, $\varepsilon^a$. This linear estimate also minimizes the quadratic penalty function

$$J = (\theta^a - \mathbf{p}) \cdot \mathbf{P}^{-1} \cdot (\theta^a - \mathbf{p}) + (\theta^a - \mathbf{d}) \cdot \mathbf{D}^{-1} \cdot (\theta^a - \mathbf{d})$$

where $(\ )^{-1}$ denotes the functional inverse (for simplicity the transformation functions for interpolating $\theta^a$ to the isolated locations of $\mathbf{d}$ have been omitted). Note that for a given estimate of the field $\theta^a$, J is just a single number.

If $\mathbf{P}$ and $\mathbf{D}$ have been chosen correctly, the distribution of J for repeated sampling and analysis should be a chi-squared variable. In other words, the appropriateness of the assumptions represented by the parameterizations $\mathbf{P}$ and $\mathbf{D}$, and by the prior estimate $\mathbf{p}$, can be tested by examining the penalty function J or, equivalently, by looking at the covariance of the data-analysis differences (Lorenc, 1981). The model is not only providing an estimate of our target field but is also providing an ongoing evaluation of our knowledge of the data and of the errors in our prior estimates, which may have been climatology or a model forecast.

This framework can also be extended to evaluation of model simulations (e.g., Frankignoul, 1991; Braconnot and Frankignoul, 1994). The details are not important here but the essence of the method is that a penalty function similar to that used for J above can be used to test the simulative skill of a model "forecast". With knowledge of the actual field variance and its mean we can compare model skill against a trivial model (e.g., climate) or against a known standard (e.g., a well-resolved hydrographic section).

This framework provides a true objective measure of model performance, an essential requirement for observing system development.

# IV. SCALES OF OCEAN VARIABILITY

This section discusses what is known about the space/time variability of certain climate variables or quantifiable aspects of the ocean climate system that must be measured or estimated by an ocean observing system for climate. Such climate variables include, for example, sea surface and subsurface temperature and sea surface elevation. Taken together measurements of these fields are fundamental to the determination of the:

Oceanic storage (heat, fresh water, carbon, and mechanical energy)
Oceanic transports (heat, fresh water, and carbon)
Air-sea fluxes (momentum, heat, fresh water, carbon, and perhaps dimethyl sulfide)
Circulation measures
- Estimates of water mass renewal rates
- Estimates of mass transports
- Estimates of velocities

The role of each climate variable in the determination of the quantities listed above is discussed and/or is related directly to meeting the subgoals of Section III.B.

Knowledge of the space and time scales of variability is essential for the design of an effective observing system. In the subsequent sections, the measurements necessary to describe this variability to sufficient accuracy are given. These measurements need to be sufficiently accurate to match the climate signals and be obtainable using proven and documented techniques. The space/time spectra of climatically relevant oceanic variability are in general poorly known at present. Our ability to define resolution and accuracy requirements for an observing system will improve with time, as we gain a deeper understanding of the scales of variability and physical processes that determine them. One important result of the observing system will be to provide the data base necessary to improve our knowledge of this spectrum of variability, so that the future design of climate observing systems can be more firmly based on quantitative statistical/dynamical information.

## IV.A. Scales of Surface Variability

The needs for, and the scales of variability of, the air-sea heat and momentum fluxes and the ocean surface properties that determine those fluxes are discussed in this section. These issues have been discussed in detail in OOSDP Background Report No. 3 (Weller and Taylor, 1993). Surface fluxes of carbon are discussed in Background Report No. 2 (Merlivat and Vézina, 1992) and in Section IV.G; surface variability in the sea ice zones is discussed in Section IV.F and the OOSDP Background Report, Sea Ice in the Global Climate System: Requirements for an Ocean Observing System (Allison and Moritz, 1995).

Surface fluxes can be estimated either by direct measurements or through the assimilation of a variety of data into atmosphere and/or ocean models. SST is a key variable for computation of surface fluxes. Air-sea temperature difference and wind speed determine the rate of exchange of sensible heat. Incoming solar (shortwave) radiation is partly reflected from the sea surface and mostly absorbed in the upper few meters, with the depth at which it is absorbed determined by the optical properties of the water. The ocean surface, which is warmed by the net shortwave flux, loses heat by infrared radiation. Some infrared (longwave) is reflected back down by the clouds or absorbed and emitted by atmospheric water vapor, but the net longwave flux, like the latent and the sensible heat fluxes, typically shows a loss of heat from the ocean to the atmosphere.

# IV. SCALES OF OCEAN VARIABILITY

## IV.A.1. Evaporation, precipitation, and salinity

The loss of water from the sea surface to the atmosphere is determined by the boundary layer gradients and the near-surface wind speed. As expressed by the bulk formula, the humidity gradient is approximated by the difference between the saturation specific humidity at the air-sea interface (determined by the sea surface temperature) and the specific humidity at some height (e.g., 10 m). The lowest specific humidities tend to be found where wind flows from a continental to maritime regime. Thus, the strongest evaporation tends to occur downwind of coastlines. Because the moisture carrying capacity of air is a strongly increasing function of temperature, warmer waters also tend to experience greater evaporation. Thus, mid-latitude western boundary currents, where relatively warm water encounters strong dry continental winds, tend to be sites of enhanced water loss. Evaporation in the vicinity of the Gulf Stream is estimated to be up to 3 m/yr. Similar amplitudes are reached in the trade wind regions, as they feed moisture into the Intertropical Convergence Zone (ITCZ). Because the atmospheric boundary layer temperature and humidity structures are more closely in equilibrium with the SST, evaporation tends to more moderate values in mid-gyre regions.

Whereas evaporation has large scales of spatial variability determined by large-scale atmospheric weather patterns, precipitation has very small space and time scales, especially in low latitude convective cells. This presents a formidable sampling problem, even on land. Short, intense rain events may provide most of the precipitation in a monthly or interannual accumulation. Such sampling difficulties mean that remote sensing techniques will be required for an observing system. Promising satellite techniques include infrared, passive microwave, and rain radars (these are discussed in Section V.C.2). However, since all techniques are indirect estimators, calibration against ground truth will be essential.

Due to the lack of direct rainfall measurements at sea, our knowledge of climate scale variations in marine precipitation is presently limited to inferences from climatologies developed from the "present weather" reports from ships at sea. By calibrating rain frequency, type, and intensity reports against island and coastal data, Dorman and Bourke (1979, 1981) have developed precipitation maps for the Atlantic and Pacific Oceans. In their annual average estimates in the North Atlantic, they find precipitation to vary from nearly 3 m/yr in the central equatorial regions to less than 10 cm/yr, just 1000 km northward, in the area west of the Sahara desert. Horizontal gradients of comparable strength occur near the Gulf Stream, where the peak precipitation exceeds 1.5 m/yr. Since these are derived from 30-year climatologies, the amplitudes and gradients in any one monthly time interval could be much larger. A large interannual cycle in tropical precipitation exists, due to the migration of the ITCZ (Yoo and Carton, 1990). This yields a double maximum between 0°-10°N in the Atlantic and Pacific (Legates and Willmott, 1990). Summer monsoons dominate the annual rainfall cycle in the far east.

SSS is correlated with estimates of net evaporation minus precipitation. High salinity regions are good indicators of dry conditions over the ocean; low salinities indicate net precipitation or high river flows. However, the data base for SSS is much poorer than that for SST; it is not routinely measured on VOS, and there is no remote sensing technique. The improvement of the SSS data base must have high priority because it is an important constraint on ocean models, an indicator of freshwater capping, and may have predictive uses in the tracking of high latitude salinity anomalies that could affect regional climate.

## IV.A.2. Scales of surface fields and fluxes

When sampled at frequencies of up to four samples per hour for a duration of several months to a year, the frequency spectra of the atmospheric and oceanic surface variables, and of the air-sea fluxes are generally red (Figure IV.A.2-1); i.e., the variability is more energetic at lower

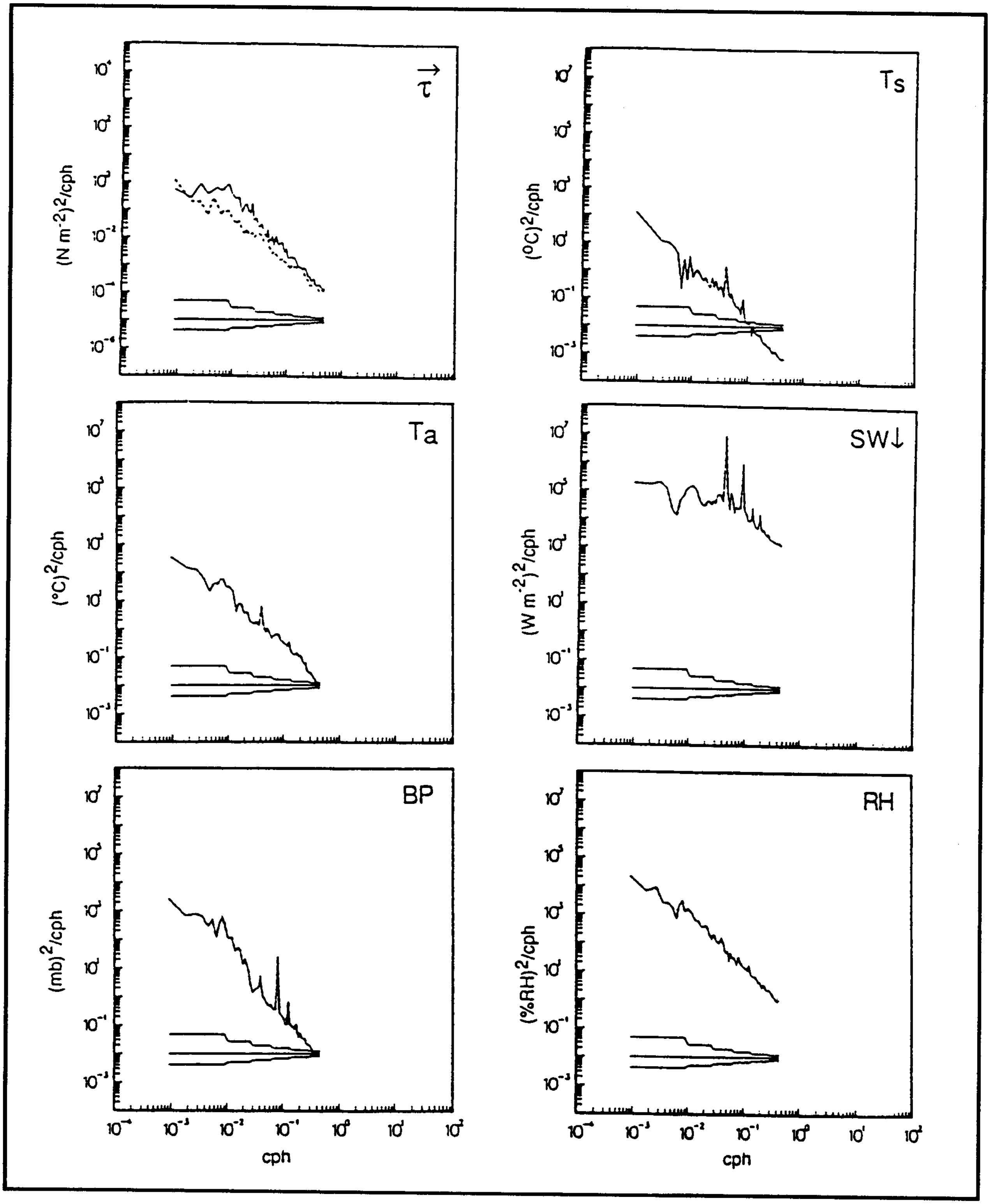



Figure IV.A.2-1. Clockwise and counterclockwise components of the rotary spectra of wind stress ($\tau$), air temperature ($T_a$), barometric pressure (BP), SST ($T_s$), incoming shortwave (SW↓), and relative humidity (RH) observed by a surface buoy moored in the mid-Atlantic for five months at 27°N, 70°W (from Weller et al., 1991).

frequencies. SST also often shows strong signals at diurnal (related to the 24-hour period of the solar insolation) and synoptic weather (five- to 10-day) time scales. While this high frequency variability is not the focus of a global, climate-oriented observing system, care must be taken not to alias these signals. In addition, as discussed by Frankignoul (1985), large scale (approaching the width of the ocean basin where they are found), persistent (*e*-folding time of around three months) SST anomalies found at mid-latitudes may result from a random series of independent atmospheric events with daily to several-day time scales. Observing the SST anomaly requires much less resolution in time and space than that required to observe and understand the processes which generated the anomaly.

In some locations of the ocean, longer period waves contribute sharp spectral peaks at 20-60 day periods. Variability at similar periods is found in the atmosphere in association with atmospheric waves. Oceanic variability at order 100-day periods is associated with eddies. Monsoonal and seasonal signals are apparent both in the lower atmosphere and in the upper ocean. Multi-year variability is well-documented in the atmosphere and the ocean in association with ENSO, and there is increasing evidence of other interannual variability in the surface variables and air-sea fluxes.

Energetic mesoscale eddy variability, with scales of 50 to hundreds of km, is to be anticipated in most locations in the ocean. Smaller scale (tens of km) variability is typically localized, found at oceanic fronts, at the equator where meridional scales are small, or in association with bottom topography and coastlines. At the equator, zonal scales in the ocean are large, reaching the width of the ocean basins.

<u>Short time scales (less than 10 days).</u> SST can be strongly affected by solar radiation. When heating occurs at low winds and clear skies, buoyancy forcing during the day creates a shallow surface layer isolated from the ocean below (Price et al., 1986). The near surface temperature in the early afternoon can be up to 3°C warmer than the bulk, mixed-layer temperature; yet, by the middle of the night, the near surface and bulk temperatures will be the same. This SST increase depends on wind stress and insolation. The SST field shows areas of diurnal warming closely matched in size, shape and orientation to the clear, calm centers of atmospheric high pressure systems (Stramma et al., 1986)—variability on space scales of 100 to 500 km. This diurnal warming effect is separate from, and normally exists with, the presence of a cool ocean surface skin formed by longwave radiative cooling and sensible and latent heat transfers from the ocean surface. This skin effect, normally a few tenths of a °C, varies on the time and space scales of the surface fluxes. The SST field may thus have spatial scales set by the atmosphere alone or by a combination of atmospheric and oceanic processes. In this way, the space scales associated with diurnal variability and synoptic variability can be linked.

Most surface meteorological variables (specific humidity, barometric pressure, insolation, wind velocity) vary with the local weather. At mid-latitudes, a spectral peak associated with the passage of synoptic weather systems (highs and lows) is observed. For example, in the mid-Atlantic, wind from the northwest typically brings drier, cooler (in winter) air off the North American continent, while wind from the southeast brings warmer, moist air. As a low moves off the North American continent and eastward across the Atlantic, change in the surface variables and fluxes is highly correlated with the direction of the local wind and thus with the passage of the low. Much of the mixing of the surface layer of the ocean may occur in association with such events. Another example is the westerly wind bursts found in the equatorial Pacific; they have five- to 10-day time scales and space scales of near 1000 km (McPhaden et al., 1992). The amount of cyclogenesis and several-day atmospheric variability differs with location and is responsible for some of the regional differences in variability of surface properties and fluxes.

Convective activity in the marine atmospheric boundary layer, which may be reflected in variability in the fluxes at the sea surface, can have both small space (1 to 10 km) and time (hours) scales. In the tropics, convection in the marine atmospheric boundary layer has a diurnal variation which is reflected in diurnal variation in cloud cover.

The oceanic response to the shortest time scales of atmospheric variability is not well documented. However, the diurnal cycle and several-day variability associated with synoptic weather systems are considered to be the major sources of short time scale variability in the upper ocean.

Small spatial scales (less than 100 km). Infrared imagery of the ocean's surface shows variability associated with major surface currents, including the western boundary currents such as the Gulf Stream, equatorial currents, and others. Some of this has scales of less than 100 km. SST is not often determined solely by local atmospheric forcing; it is set by a balance of atmospheric and oceanic processes, including wind-driven mixing, atmospheric heating and cooling, and horizontal and vertical advection in the ocean. Oceanic processes give rise to small scale variability with longer persistence times than the variability associated with such scales in the atmosphere. Ocean fronts have widths of 10-50 km. They are found in several locations: collocated with atmospheric convergences, such as between the Westerlies and Trades in the Subtropical Convergence Zone (STCZ); in association with shoaling bottom topography; and at the edge of strong boundary currents. Across such fronts, both temperature and salinity can change rapidly. Fronts are often recurrent within a given region, though their exact positions may vary. Fronts southwest of Bermuda are found between 25°N and 30°N (Weller et al., 1990); 1°C to 2°C change in sea surface temperature and 0.5 change in surface salinity in approximately 10 km in the cross-frontal direction and along-front scales of 100s of km were observed. In the Southern Ocean, the Subtropical Front, Subantarctic Front, and Polar Front are relatively fixed in position over time, but still may move latitudinally (of order 100 km) in some regions.

Associated with fronts can be eddies with scales of 10s of km down to 5 km (Gascard, 1978). Filaments and jets are found near fronts and also with boundary currents; these can be 10s of km wide. For example, jets of cool, upwelled water between 10 and 40 km wide and 4°C cooler than surrounding waters have been reported off the coast of California (Rienecker and Mooers, 1989). Similar structures have been found in the Benguela Current off Namibia (Shillington et al., 1990).

In response to strong surface cooling, convection may occur in the upper ocean. In the western Mediterranean convection has been observed in areas 10s of km in width (MEDOC Group, 1970), and individual convection cells of order 1 km in horizontal extent have been reported (Schott and Leaman, 1991). Such small scale oceanic variability appears in SST. The boundary regions of the ocean basins often show smaller scales of variability in association with annual variability as well as with boundary currents and associated eddies.

Clouds can have small spatial scales. In the tropics, a variety of smaller convective events, with space scales of 100 to 200 km and less, are found. Precipitation, local winds, and local variations in air-sea fluxes are to be found in such regions. Janowiak and Arkin (1991) show rainfall maps based on satellite cloud-top temperatures for three successive winters spanning the 1986-1987 warm ENSO event to the following cool event in 1988-1989. Based on these results, relatively small-scale sampling (down to 2° x 2°) may be required to resolve local maxima in rainfall. The WCRP Global Precipitation Climatology Project (GPCP) (WMO, 1991a) is presently using surface data as well as data (infrared and microwave) from geostationary and polar orbiting satellites to investigate the characteristics of precipitation and produce monthly estimates of precipitation on a 2.5° x 2.5° grid. Away from the tropics, where the mean winds are higher, the impact of individual atmospheric convective features on the surface of the ocean and the air-sea fluxes is less well documented.

Sub-seasonal (10- to 180-day period) variability. At time scales greater than diurnal and synoptic but shorter than the annual periods, the spatial scales of variability are in general larger. Atmospheric circulation has anomaly patterns with scales of 1000 km and larger that sometimes show variability correlated with anomalies at remote locations. These monthly to seasonal atmospheric fluctuations influence storm tracks and heat fluxes (Cayan, 1992a, b).

Colossi and Barnett (1990) examined the scales of SST measured by drifting buoys deployed from 15° to 60°S in the Southern Oceans. The distances associated with the two-dimensional correlation dropping to less than 0.05 (essentially 0.0 based on 95% confidence level) given by them for SST were: greater than 2800 km zonal scales for Atlantic and Pacific summer SST, 1600 km meridional scales for Atlantic and Pacific summer SST, 1600 km and 2800 km zonal scales, respectively, for Atlantic and Pacific winter SST, and 1200 km and 1600 km meridional scales, respectively, for Atlantic and Pacific winter SST.

Thirty- to sixty-day variability is found in the tropics associated with atmospheric waves (Madden and Julian, 1972; Lau and Chan, 1988). The interrelation between the 30- to 60-day waves, westerly wind bursts, and ENSO remains a topic of ongoing research. Evidence has been found in the SST field of long waves (800- to 1200-km wavelength) with 20- to 30-day periods in the equatorial Pacific (Legeckis, 1977; Philander et al., 1985). Halpern et al. (1988) found surface velocity oscillations in the equatorial Pacific with a period of 20 days, wavelengths of 1300 and 1600 km, and westward phase speeds of 0.8-0.9 m/s. The waves were seasonally modulated (stronger in the summer to fall) and not present during an El Niño. Reverdin and Luyten (1986) have found similar waves in the western equatorial Indian Ocean, characterized by 26-day period, a wavelength of 1000 km, and westward phase propagation of 0.4 m/s. In addition to the 26-day waves, longer period oscillations have been reported south of the equator in the Indian Ocean. Legeckis and Reverdin (1987) report the signature of equatorial waves (1000-km wavelength, 24-day period) in the SST field in the eastern equatorial Atlantic. In the eastern Atlantic, Weisberg's (1984) analysis of surface currents shows a wave with 25-day period, 1140 km wavelength, and westward phase propagation of 0.5 m/s at 15°W in the equatorial Atlantic. This was supported in deep current records analyzed by Weisberg et al. (1979).

Mysak and Mertz (1984) reported 40- to 60-day variability in temperature and velocity in the Somali Current; and Duing and Schott (1978) reported 50-day oscillations in the South Equatorial Current of the Indian Ocean. Mysak and Mertz (1984) suggested that the 40- to 60-day waves were forced by atmospheric variability at the same period, but Kindle and Thompson (1989) believe that barotropic instability of the currents in the region is the source of the waves.

Molinari et al. (1992) have summarized the findings of a number of studies of the spatial and temporal scales of variability of SST in which sub-seasonal temporal averaging of the data was used; Table IV.A-1 is adapted from them. They suggest caution in interpreting results from these studies, noting that the averaging used in preparing data will act as a filter. They note that using averaged data (2° latitude by 10° longitude, three month) White and Bernstein (1979) found a zonal scale of variability for SST in the central Northern Pacific of 2900 km; in contrast, use of synoptic data (spatial scales of 80 km) yields a dominant zonal scale of 1500 km.

Mesoscale variability (hundreds of km). The spatial distribution of mesoscale currents and their variability can be obtained from sea surface elevation as recorded by satellite altimeter data (see also discussions in Sections IV.C and IV.D). Figure II.A-1 shows a global distribution of ocean surface height variability derived from TOPEX/POSEIDON altimetry data (Tapley and Shum, personal communication, 1994). Mesoscale variability is generally greater near major current systems and fronts, and, in some locations is forced directly by the atmosphere. In many locations, mesoscale current variability is reflected in the SST field.

| Study | Region of study | Time averaging in study | Spatial averaging in study | Time scale of SST field | Spatial scale of SST field |
|---|---|---|---|---|---|
| Colosi and Barnett (1990) | S. Atlantic | 1 day | 400 km lat.<br>400 km lon. | | summer:<br>1600 km. lat.<br>>2800 km lon.<br>winter:<br>1200 km lat.<br>1600 km lon. |
| | S. Pacific | 1 day | 400 km lat.<br>400 km lon. | | summer:<br>1600 km lat.<br>2800 km lon. |
| Festa and Molinari (1992) | Atlantic | 30 day | 100 km lat.<br>100 km lon. | | 1700 km lat.<br>1700 km lon. |
| Meyers et al. (1991) | Tropical Pacific | 60 days | 200 km | 85 days | 550 km lat. |
| Phillips et al. (1990) | Indian | 60 days | 200 km lat. | 78 days | 600 km lat. |
| Sprintall and Meyers (1991) | E. Pacific | 60 days | 200 km lat.<br>1000 km lon. | 90 days | 600 km lat.<br>3100 km lon. |
| White and Bernstein (1979) | N. Pacific | 90 days<br><br>synoptic | 200 km lat.<br>1000 km lon.<br>80 km | 300 | 1500 km lat.<br>3000 km lon.<br><br>1500 km lon. |

Table IV.A-1. Spatial and temporal scales of variability in sea surface temperature (after Molinari et al., 1992).

Analysis of five years (1979-1984) weekly 1° by 1° gridded sea surface temperature data (from satellite) in the Tasman Sea (Tate et al., 1989) showed the largest variances ($\approx 0.8(°C)^2$) associated with the East Australian Current and variances of $\approx 0.4(°C)^2$ in the region between New Zealand and Australia. There was a strong seasonal cycle. With the seasonal cycle removed the characteristic time scale of the weekly mean sea surface temperature anomalies was between 80 and 200 days, smallest near the East Australia Current and largest near New Zealand. Near Australia characteristic space scales for the weekly mean sea surface temperature anomalies were 125 km, while away from Australia and closer to New Zealand the spatial scales were between 250 and 400 km.

Through the analysis of SST fields spanning ocean fronts, Halliwell and Cornillon (1989) found evidence of larger scale temperature anomalies, with spatial scales of 800 km and up, a time scale of approximately 275 days, and an amplitude of 1°C. Monthly or seasonal anomalies in sea surface temperature have scales of 500-km and larger have been found elsewhere. These anomalies persist for longer than three months, and are related to atmospheric forcing (Frankignoul, 1985; Cayan, 1992b). 500-km and greater scale variability in the flux fields also has annual and longer time scales (Zhao and McBean, 1986; Cayan, 1992a). Heat flux anomalies have magnitudes that sometimes exceed 500 W/m$^2$. Latent and sensible heat flux dominate the anomalies away from the tropics. In the tropics, solar and latent heat flux contribute. Cayan (1992c) has calculated EOFs of the anomalies in the sensible and latent flux fields using four decades of data. The four most energetic spatial modes of the sum of latent plus sensible heat describe 50% of the variance and have regional (a fraction of the ocean basin, up to 1000 to 2000 km) maxima with magnitudes of up to 50 $W/m^2$.

Variability at 100 km spatial scales in the ocean is found at times associated with atmospheric forcing with similar scales but more often associated with the natural variability of the oceans. Umatani and Yamagata (1991) point out the strong, jet-like winds that flow through passes in Central America and out over the eastern equatorial Pacific. Associated with the seasonal north-south migration of the ITCZ and the related change in the strength of the jets, there is intensification in the wind stress curl on scales of roughly 200 km. These winds drive eddies in the upper ocean along the coast of Central America with radii as small as 300 km.

Annual variability. The annual signal is strong in surface variables. SST exhibits seasonal cycles that are more pronounced with distance from the equator. The annual cycles in both SST and SSS are closely related to the annual cycles in local heat storage, deep convection, and freshwater flux. Thus, they reflect the influence of both atmospheric forcing and ocean mixed layer dynamics.

Strong monsoonal variability in the surface winds and related air-sea flux fields (sensible and latent heat flux) dominates some regions of the ocean. In the Arabian Sea, the monsoonal cycle in the atmosphere forces variability on the same time scale in the surface velocity and temperature fields (Hastenrath and Greischar, 1991; Bauer et al., 1991). In the central Arabian Sea there is a mid-summer decrease in sea surface temperature collocated with the wind maximum associated with increased evaporative cooling (McCreary and Kundu, 1989). The response along the coasts has smaller scales. Along Somalia, for example, strong along-shore currents and cooler SSTs associated with local upwelling are found (McCreary and Kundu, 1989; Hastenrath and Greischar, 1991). Water several degrees colder than that offshore can be localized within a few 10s to 100 km of the coast. This small spatial scale in SST is in turn reflected in the sensible heat flux field. Potemra et al. (1991) showed seasonal model variability in the Bay of Bengal in response to monsoonal forcing.

As a result of seasonal changes in incoming solar radiation and the associated changes in atmospheric circulation patterns, strong annual variability is also prevalent outside the monsoon regions. The strongest signal is usually found in SST, especially at mid and high latitudes. For example, Lie and Endoh (1991) report that the SST field in the northwest Pacific (0°-44°N, 120°E-180°) is dominated by annual variability while, in contrast, the subsurface temperature fields below 100 m are characterized by dominant interannual variability. The annual signal in SST is strongest away from the tropics.

Delcroix and Hénin (1991) have examined surface salinities from 1969 to 1988 along four shipping lanes in the tropical Pacific. Surface salinities were lowest north of the equator with a range of approximately one along the track lines (in the domain bounded by 28°N and 28°S and between 80°W and 140°E), and seasonal variability of up to 0.3 was found at any given latitude along the tracks. Near the ITCZ and South Pacific Convergence Zone (SPCZ), the seasonal variability in surface salinity was consistent with the seasonal signal in rain. In the tropical Atlantic, evaporation has little latitudinal dependence, but precipitation has a strong maximum collocated with the ITCZ (Yoo and Carton, 1990).

Annual mean fields. Maps of the annual mean SST have been published and show large spatial scales with the exception of special regions, such as the western boundary currents discussed above (Bottomley et al., 1990; Reynolds, 1988; Levitus, 1984).

A map of the net freshwater flux (evaporation minus precipitation or E-P) for the North Atlantic from Schmitt et al. (1989) shows the spatial scales of this field (Figure IV.A.2-2). Zonally

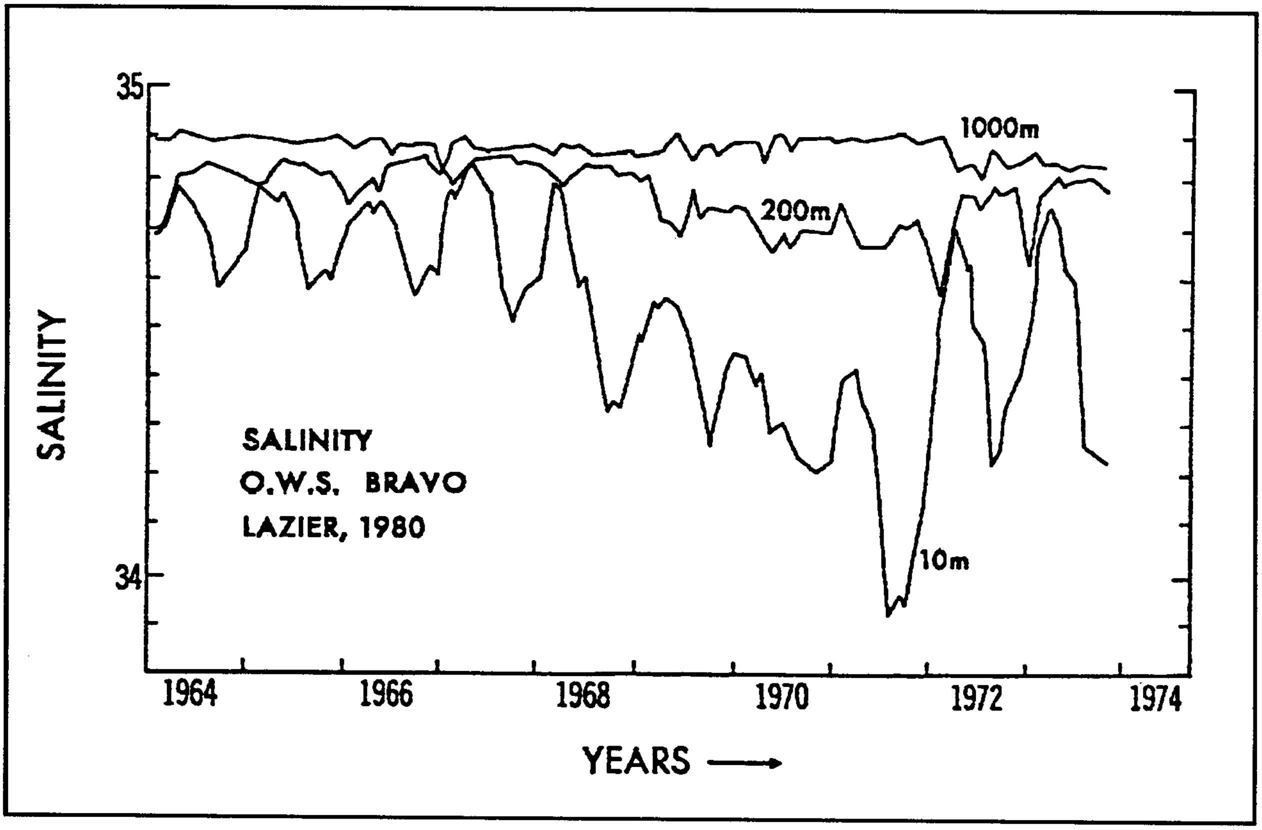



Figure IV.A.2-2. Salinity (measured using the Practical Salinity Scale) as a function of time at 10, 200, and 1000 m at OWS Bravo in the Labrador Sea (Lazier, 1980).

averaged precipitation (Gates, 1987) has an equatorial peak and two lesser maxima at approximately 40°N and 50-60°S. Maps of climatological precipitation (Jaeger, 1976) illustrate that meridional variability is to be expected within these zonal maxima. In the western Pacific, in particular, maxima with 500 to 1000 km scales are apparent.

Numerical weather prediction models produce gridded fields of the air-sea fluxes. 1.875° gridded fields produced by the European Center for Medium Range Weather Forecast (ECMWF) model for 1983-1985 have been examined by Simonot and Le Treut (1987); spatial distributions of the fluxes agreed with climatological maps, but biases were found for shortwave radiation (20 $W/m^2$), latent heat flux (40 $W/m^2$), and net heat flux (40 $W/m^2$). Using the same data but an improved model, Barnier and Simonot (1990) have examined the surface fields for 1986. Maps of the global annual latent heat flux and annual net heat flux (Figure IV.A.2-3) for 1986 show the spatial scales of the model fields. A bias of 5 $W/m^2$ is still thought to exist in the net heat flux, as well as problems with computing net shortwave associated with parameterization of clouds. Barnier and Simonot (1990) also examined the spatial variability of the low frequency (less than 0.1 cpd) net heat flux. In both oceans, roughly 80% of the variance in the annual net heat flux was associated with the first five EOFs.

Interannual variability. Variability at periods of longer than one year is known to exist and has been well documented for ENSO. Enfield's (1989) review of El Niño indicates evidence for El Niño events dating back to the 1550's. The Southern Oscillation is a large scale change in surface barometric pressure with an associated change in air temperature and precipitation, while the El

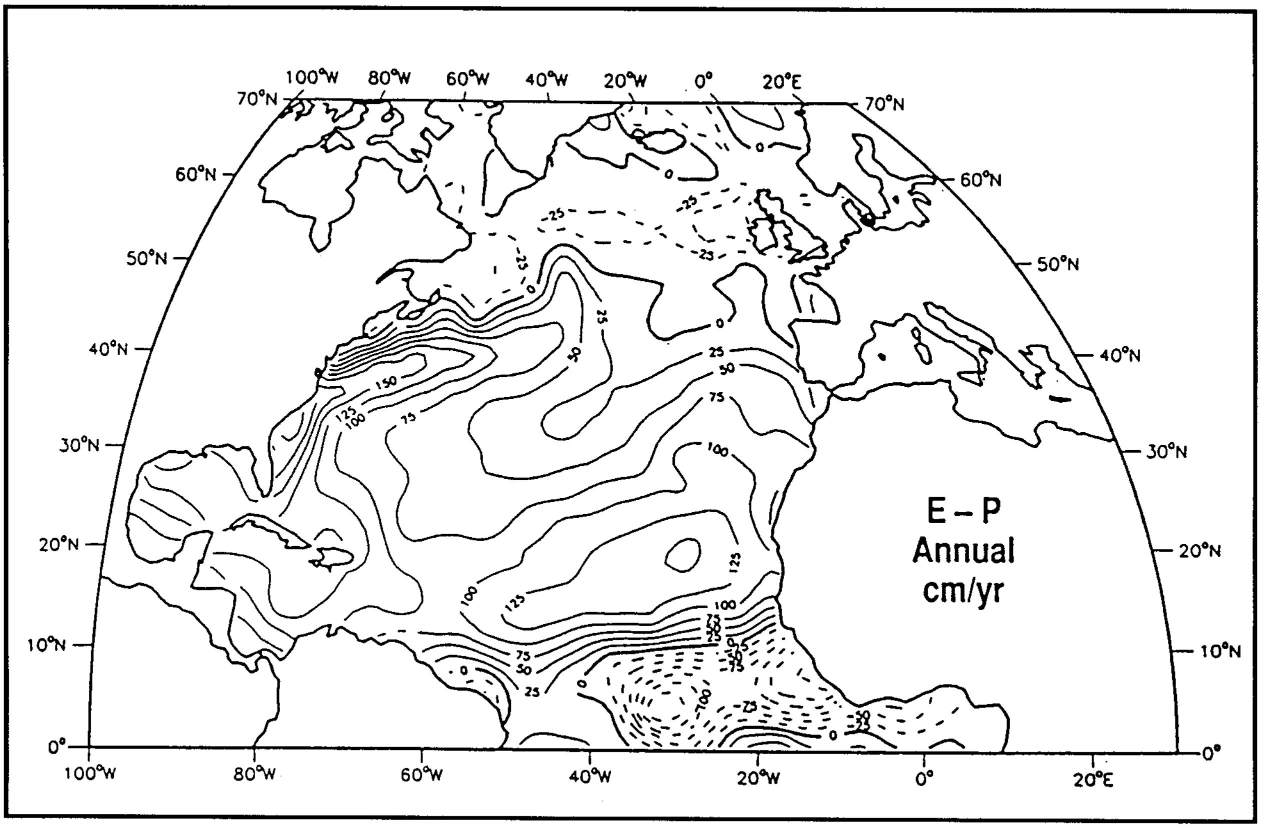



Figure IV.A.2-3. Annual average evaporation minus precipitation (E-P) map from Schmitt et al. (1989). Error bias not known.

Niño is the related oceanic variability, most apparent in SST in the equatorial Pacific (Trenberth, 1991). These events occur approximately every two to seven years. At the equator, the signal associated with El Niño is dramatic. Monthly mean temperature anomalies in the eastern Equatorial Pacific reached 5.6°C during the 1982-1983 El Niño (Gill and Rasmusson, 1983) and 3.4°C during the 1986-1987 El Niño (McPhaden and Hayes, 1990). The spatial scales associated with ENSO events are relatively large—approximately 60° longitude and 30° latitude as suggested by the zonal wind stress for 1970-1985 derived at Florida State University. The first two EOFs of this data exhibited approximately these scales and included 31 and 19% of the variance respectively (von Storch et al., 1989).

Delcroix and Hénin (1991) examined SST and SSS variability in the southwestern tropical Pacific (10°S to 24°S, 140°W to 160°E) over the years of 1975-1985. The annual mean SST field had a meridional gradient and little zonal variability; interannual variability showed smaller zonal scales. Much of the variance in SST (82%) was captured by the first EOF which had a strong annual signal. Local Ekman pumping and evaporative cooling were thought by Delcroix and Hénin (1989) to play a significant role in creating anomalies in the SST field seen during the 1982-1983 ENSO. The mean SSS field did not show the zonal orientation of the temperature field, and the interannual variability of the salinity field had maxima located along the characteristic location of the SPCZ. Less variance (46%) of the SSS was associated with the first EOF. The SSS field was highly correlated with the freshwater flux field from two to three months prior. During non-El Niño periods, the seasonal migration of the SPCZ and its associated precipitation was responsible for the observed annual cycle in SSS. Anomalous surface salinities during the 1982-1983 El Niño were related to an equatorial shift in the SPCZ.

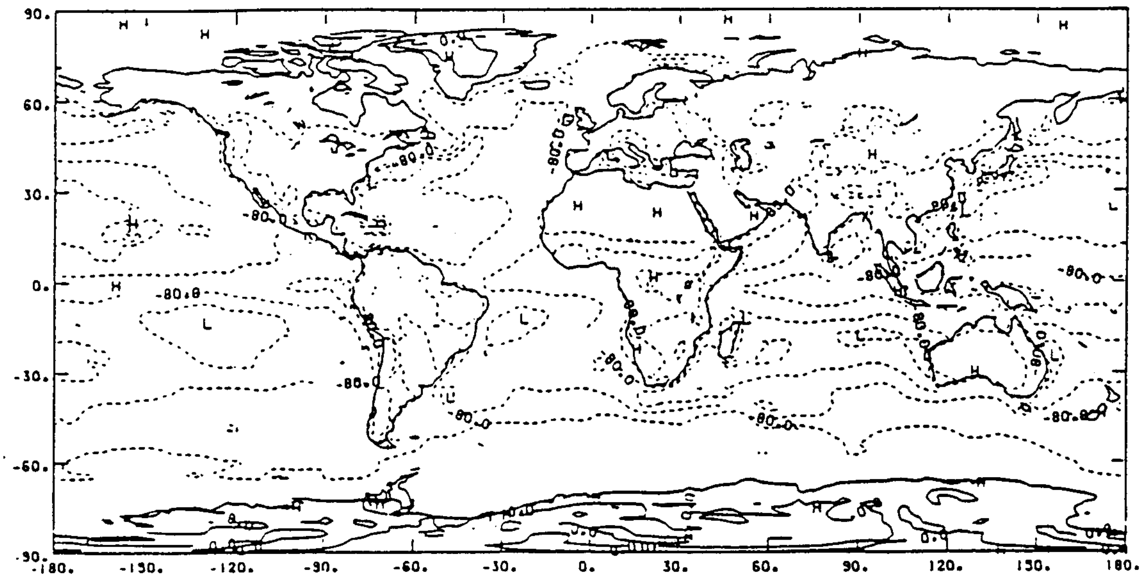
Philander (1986) reports that interannual variability in coupled atmosphere-ocean interaction in the Atlantic is, due to the smaller basin size, more episodic than in the Pacific. Trenberth (1991) notes that in addition to its smaller size (and smaller size of the warm reservoir on the western side of the basin), the zonal contrast along the equator is less in the Atlantic and that a feature equivalent to the SPCZ is not found in the Atlantic. However, he does cite an El Niño-like event in the Atlantic in 1984 when anomalies in SST reached 4°C and reports that changes in Atlantic SST influence rainfall over the adjacent continents. Interannual variability in the surface meteorological fields can be reflected in the surface oceanographic fields. Zebiak (1993) has shown that interannual variability in the upper layers of the Atlantic has a component with ENSO-type characteristics.

Cadet and Diehl (1984) investigated interannual variability of the surface fields over the Indian Ocean using data from 1954 to 1976. The interannual variability had spatial scales comparable to the size of the ocean basins in the region; temporal variability was found on time scales longer than the Southern Oscillation. They speculate that the observed variability is consistent with a 20-year cycle for which they cite several other supporting references.

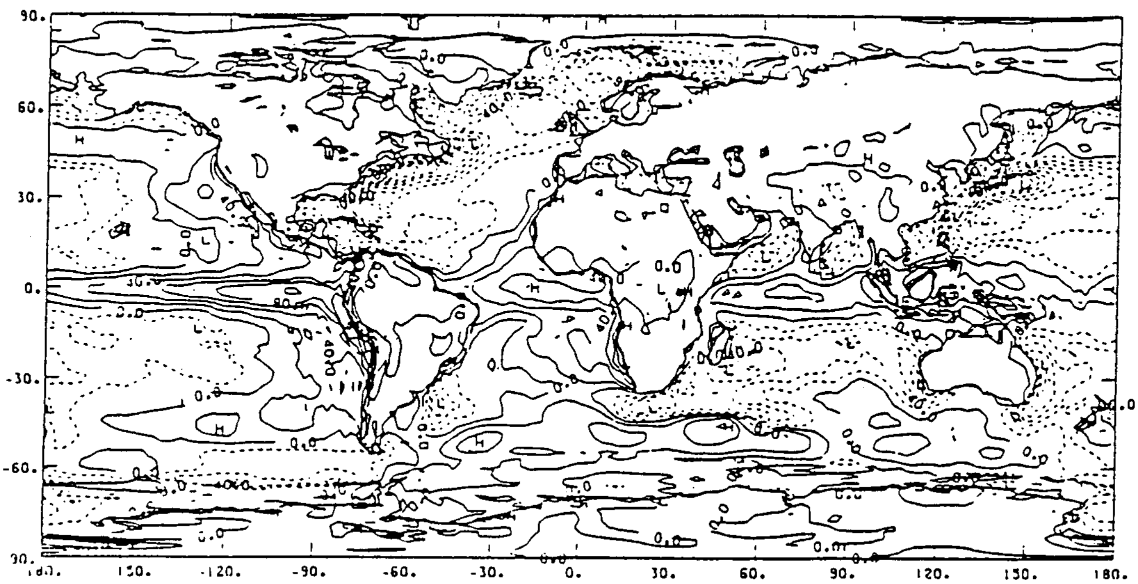
Figure IV.A.2-4 suggests that the high latitude annual cycle in SSS can be of order 0.2 and the interannual signal as large as 0.8, due to the passage of the "Great Salinity Anomaly". (Schmitt and Bryan (1991) suggest that the Great Salinity Anomaly could have been formed by a 20% increase in the annual discharge of ice through Fram Strait.) Interannual variability of the surface salinity field in the North Atlantic is also documented by Levitus (1989a, c). His contrast of surface salinities from 1955-1959 with surface salinities from 1970-1974 shows change in excess of 0.5 in some locations. Unfortunately, not many oceans are as well sampled as the North Atlantic.

Decadal and longer time scales. Yamagata (1991) notes the presence of a quasi-biennial oscillation and a decadal-scale trend in the upper ocean heat content in the western Pacific. Royer (1989) analyzed temperature and hydrographic data from the northeast Pacific and found evidence for variability in SST with a period of approximately 28 years. This signal, with an amplitude of 1.5°C, was not related to ENSO. Nor could it be correlated with changes in oceanic circulation. Servain et al. (1990) compared two SST data sets from the tropical Atlantic Ocean; one was based on data from 1911-1972, the other included data from 1964-1984. After correcting for differences associated with different measuring techniques, they report net warming with time south of the equator of up to 1.25°C per century, a net cooling, however, near the coast of Africa. North of the equator, much of the region showed net cooling of approximately 0.25°C per century.

In addition to the diurnal signal and the several-day variability associated with synoptic weather, the magnitude of the incoming shortwave radiation at the sea surface shows small, many-year period variations associated with change in the sun's output. Periodic variations such as the 1.5 $W/m^2$ amplitude signal over 11 years, variations associated with sunspots, and longer term changes of order 1 $W/m^2$ over a few centuries have been reported (WMO, 1991b). Friis-Christensen and Lassen (1991) present evidence that the length of the sunspot cycles is highly correlated with Northern Hemisphere temperature anomalies over the duration of the available temperature data (last 130 years) and with records of sea ice around Iceland back to 1740. Apparent in the sunspot cycle length time series is a period of 80-90 years. However, lack of historical data about the magnitude of the sun's total irradiance on these long time scales makes it difficult to prove the influence of such variability on global change (Kerr, 1991). There is evidence of long term variability in other surface fields. The second (7.4% of the variability) and third (6.8% of the variability) EOFs of Lau and Sheu's (1991) analysis of global rainfall anomalies were associated with periods of approximately 100 and 60 years, respectively.



a) Annual latent heat flux



b) Annual net heat flux

Figure IV.A.2-4. Annual average for August 1985 through July 1986 of a) latent heat flux and b) net heat flux from ECMWF (Barnier and Simonot, 1990). The contour interval is 40 W/m$^2$ for the latent heat flux and 20 W/m$^2$ for the net heat flux; solid lines indicate heat flux into the ocean.

## IV.A.3. Guidelines for sampling requirements, timeliness, and accuracy

The surface component of the observing system must address many aspects of the spatial and temporal variability summarized above. Strong high frequency and high wavenumber variability represents a substantial challenge if accuracies matching those required to investigate climate change are required. Temporal sampling at up to four times a day may be supported in some locations already, driven by the need for model initialization for weather forecasting. Regions of strong variability at small spatial scales present a similar sampling problem.

One approach to the problem of developing a sampling strategy is to use the statistics, space and time scales of variability, climatologies, or other information available about the fields to be sampled. Legler (1991), for example, has used moored buoy data from two equatorial and two mid-latitude sites to estimate the number of observations needed to compute accurate five- and 30-day mean values of the SST. The data were assumed to have no biases or other systematic error associated with the sensors. Calculations were made of the number of observations required to obtain an accuracy of 0.1°C, 0.2°C, 0.5°C, and 1°C. Table IV.A-2 summarizes the results for 0.1°C and 0.2°C. For the temperature data, Legler (1991) found that the following relationships between the number of data points required and the standard deviation of the data fit:

$$N_{0.1} = 1.0\text{-}4.5\sigma+458\sigma^2,\ R=0.837$$

$$N_{0.2} = 1.0\text{-}2.21\sigma+99.3\sigma^2,\ R=0.977$$

$$N_{0.5} = 1.0\text{-}3.2\sigma+16.2\sigma^2,\ R=0.990$$

$$N_{1.0} = 1.0\text{-}0.26\sigma+3.5\sigma^2,\ R=0.994$$

where $\sigma$ is the standard deviation of hourly means during the five- and 30-day periods, and R is the correlation coefficient. The results were independent of the location of the data and the length of the averaging interval. Legler (1991) points out that mid-latitude locations, with higher values of $\sigma$ for wind velocity, require corresponding larger numbers of data.

Carter (1992) has pointed out that the calculations of Legler (1991) or Halpern (1988) only address the problem of how well a sub-sampled data set represents a complete set of samples; they ignore any error between the complete set of samples and the true value. Thus, their estimate of the number of samples needed is likely to be too low. Also, in randomly sub-sampling the data set, any correlation between the original samples is lost. For independent samples the accuracy attained is (for large n) given precisely by:

$$\text{accuracy} = \frac{1.96\ \sigma}{n^{0.5}}$$

where accuracy is defined by the 95 percentile and $\sigma$ is the standard deviation of the n samples. This yields required numbers of observations for a given accuracy in reasonable agreement with those given in Table IV.A-2.

In the polar regions, data are sparse and sampling plans less easily developed from existing information.

The need for some surface data to initialize models places demands on how soon the data must be accessible as well as on its accuracy. Accuracies and sampling characteristics of the sea surface temperature used for NWP have been identified as 0.5°C on a 100-km spatial and three-day temporal grid. The products are needed in real time.

| Location | 0°, 152°W | 0°, 95°W | 34°N, 70°W |
|---|---|---|---|
| 30-day period | | | |
| $N_{0.1}$ | 85 | 449 | 356 |
| $N_{0.2}$ | 20 | 108 | 54 |
| 5-day period | | | |
| $N_{0.1}$ | 42 | 54 | 52 |
| $N_{0.2}$ | 11 | 23 | 18 |

Table IV.A-2. Number of observations to achieve an accuracy of 0.1°C ($N_{0.1}$) and 0.2°C ($N_{0.2}$) in SST (from Legler, 1991).

In planning sampling of the air-sea interaction fields for WOCE (Large, 1985) spatial sampling of 5° longitude by 2° latitude was recommended for the tropics and 5° longitude by 5° latitude outside the tropics. Further, it was recommended that the seasonal cycle be resolved, with the sampling making available monthly means and statistics. The motivation for this sampling strategy in WOCE was to provide the data to force eddy resolving, global ocean general circulation models with observed air-sea fluxes. WOCE sampling requirements for SST were 0.5°C accuracy, 5° x 5° resolution, 30-day temporal resolution.

For TOGA with its focus on the interaction between the tropical ocean and the global atmosphere, the temperature of the sea surface is of critical interest. Requirements for the spatial and temporal sampling as well as for the accuracy of tropical SST were set as 0.3-0.5°C, 15-day temporal resolution and 2° x 2° spatial resolution and for global SST were 0.5°C, 30 day, and 5° x 5°.

The sampling schemes proposed for and implemented by WOCE, TOGA, and other large research programs form a valuable starting point for OOSDP formulation of an observing system. They do not, however, address the sampling needed in high latitude and polar regions.

For the study of climate change, frequent data or careful sampling may be necessary to avoid aliasing the strong diurnal, synoptic (weather), sub-annual, and annual signals. A reasonable target for the observing system, if aliasing could be avoided, would be monthly averages on 5° x 5° squares extratropically and on 2° x 2° or 2° x 5° (reflecting the larger zonal scales) areas in the tropics. Short time scale (hours to diurnal to several days) variability in clouds may reflect changes in convection. Several to 10-day variability in clouds results from passage of synoptic weather systems. Both can influence SST. Sampling should return an accurate monthly mean within these areas. An example of a strategy to avoid aliasing diurnal variability in sea surface temperature would be to sample during the local night. An alternative is sampling at least four times per day which may not be feasible.

Diurnal warming of the sea surface can exceed 3°C, while in mid-latitudes the seasonal signal can be 15°C. In contrast, the signal associated with the doubling of atmospheric $CO_2$ has been put at 1.5 to 2.0°C by model calculations (NRC, 1983). Hanson et al. (1989) have reported a 0.5°C warming since 1880 for the contiguous United States. Model-predicted warming varies over the globe, but using Hanson et al. (1989) as an indicator of magnitude, observing system observation of monthly, 5° x 5° SST should be accurate to 0.1°C to track such change. Such an accuracy would be sufficient to observe signals of the size of the 1°C warming of the tropical Pacific SST reported by Nitta and Yamada (1989). Pan and Oort (1983) suggest that 1°C rise in eastern Pacific SST associated with ENSO produces a rise of 0.5°C in global mean air temperature; again 0.1°C accuracy for SST would suffice. Model runs indicate, however, that the warming associated with increased $CO_2$ is neither spatially nor temporally uniform. Hansen et al. (1984) show that increases in surface air temperatures are greatest at high latitudes, with maxima in excess of 10°C north of

60°N and of 18°C south of 60°S. However, over most of the ocean, in mid-latitudes, for detection of climate-related signals, biases must be less than 0.1°C, and random error and spatial coverage should be such that monthly averages over 5° x 5° and 2° x 2° areas should achieve accuracy close to 0.1°C.

Natural climate variability in the ocean at periods longer than a year, such as ENSO or the shift in the position of the Kuroshio, will be larger in magnitude than some anticipated climate signals, but the spatial sampling of the observing system should be fine enough to prevent aliasing and allow signals to be matched with the appropriate processes. Compared to natural variability, anthropogenic climate change is small, though important because it increases the mean. The total increase to date in radiative forcing thought to be associated with man's input of carbon dioxide and other gases to the atmosphere is approximately 2 $W/m^2$ (Mitchell, 1989). Changes in precipitation associated with the doubling of atmospheric $CO_2$ are predicted to be largest (in excess of 2 mm/day) in the existing mid-latitude locations of rainfall maxima.

## IV.B. Upper Ocean Temperature and Salinity

### IV.B.1. Sampling considerations for upper ocean temperature and salinity

For the following discussion, the upper ocean will be loosely defined as waters above the permanent thermocline changing on relatively fast time scales (weeks to several years). Figure IV.B.1-1 shows typical profiles of upper ocean temperature and salinity. Salinity is a significant factor in upper ocean dynamics at very high latitudes (near-freezing temperatures and ice formation lead to a salinity-dominated stratification), in the western Pacific warm pool (very high precipitation and evaporation), and in subtropical high salinity regions (excess E-P). The regular determination of the upper ocean temperature and, to a lesser degree, salinity and velocity, is essential for progress in monitoring, understanding, and prediction of transient climate anomalies. The upper ocean is able to buffer fluxes of heat (and freshwater) on time scales of months to years, effectively providing long-term memory for the ocean-atmosphere system. Theoretically this provides upper ocean observations with some advantage over, for example, atmospheric sampling of the climate system. The buffering action of the upper ocean integrates the high-frequency signals of the atmosphere to give ocean climate signals of seasonal and longer time scales (represented schematically in Figure IV.B.1-2). These scientific advantages must be weighed against the considerable logistical problems associated with sampling the ocean so that, in practice, studies and analysis of upper ocean behavior still rely on sound knowledge of the surface heat, momentum, and freshwater fluxes.

Low-frequency variability in the large-scale thermal structure of the equatorial Pacific Ocean is one of the main characteristics of the ENSO phenomenon. Systematic measurements of the tropical oceans are needed to monitor, understand, and perhaps predict ENSO events and other tropical ocean and coupled ocean-atmosphere variations. The premise here, based on scientific research, is that upper ocean observations in the tropical region are ideal for determining the low-frequency, large-scale structure which characterizes the variability and, perhaps, provide important information for the initialization of seasonal-to-interannual coupled ocean-atmosphere prediction models. Ingestion of upper ocean data from outside the tropics is also being tried in coupled ocean-atmosphere model prediction systems, but, while the preliminary evidence strongly suggests a key role, it is premature to say what subset of upper ocean data is necessary for skillful prediction.

At subtropical and higher latitudes upper ocean temperature measurements are used to map oceanic fronts and (indirectly) ocean currents and to follow the seasonal storage, transport, and release of heat. The problem is complicated by the ubiquitous meso-scale eddies found at these latitudes. The horizontal scale of this ocean "weather" (order 100 km) makes it unlikely that a global in situ

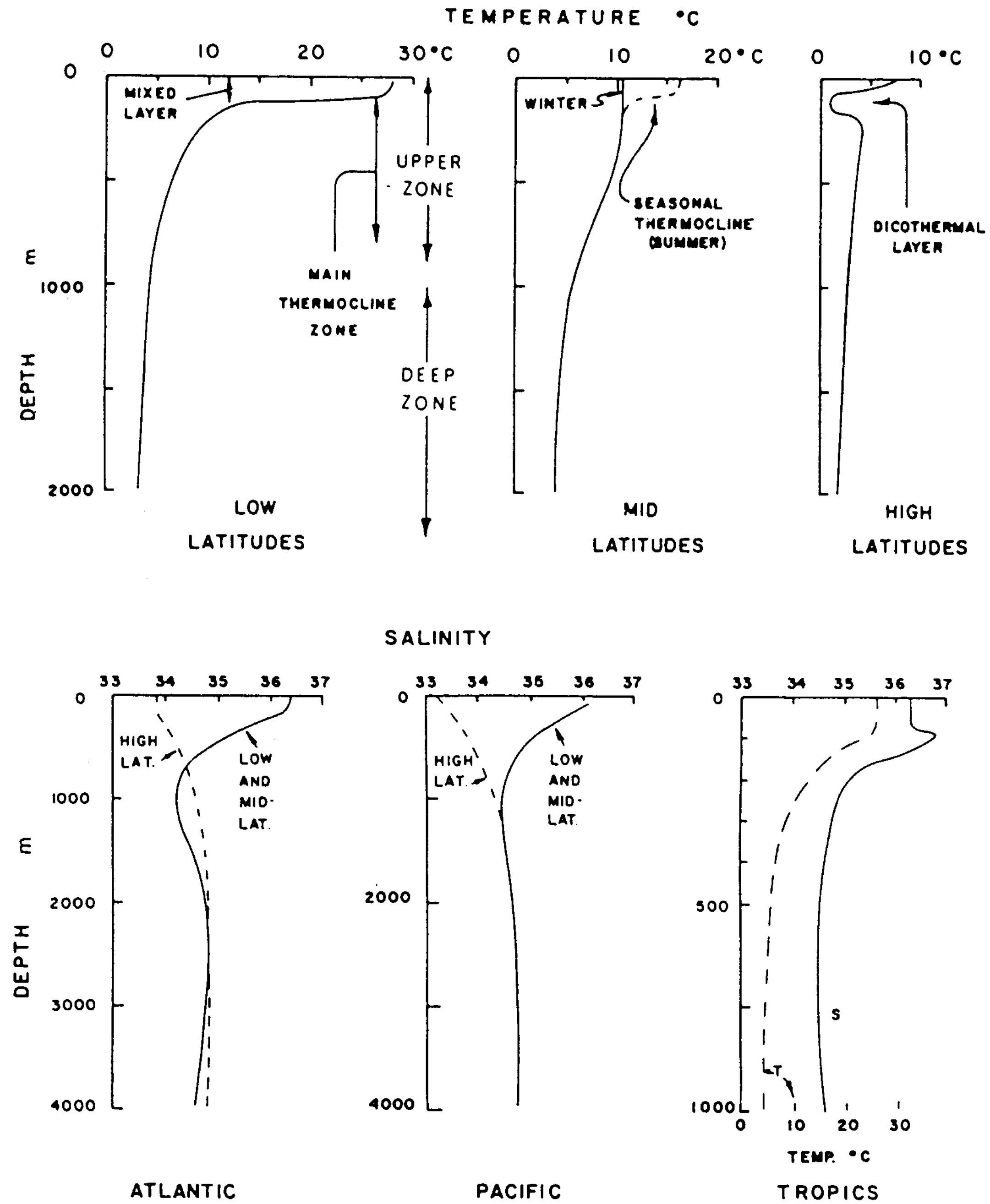



Figure IV.B.1-1. Schematic upper ocean temperature and salinity profiles for low, mid, and high latitudes (after Pickard and Emery, 1990, figures 4.4 and 4.11). The relative importance of salinity and temperature may change with season or regional effects.

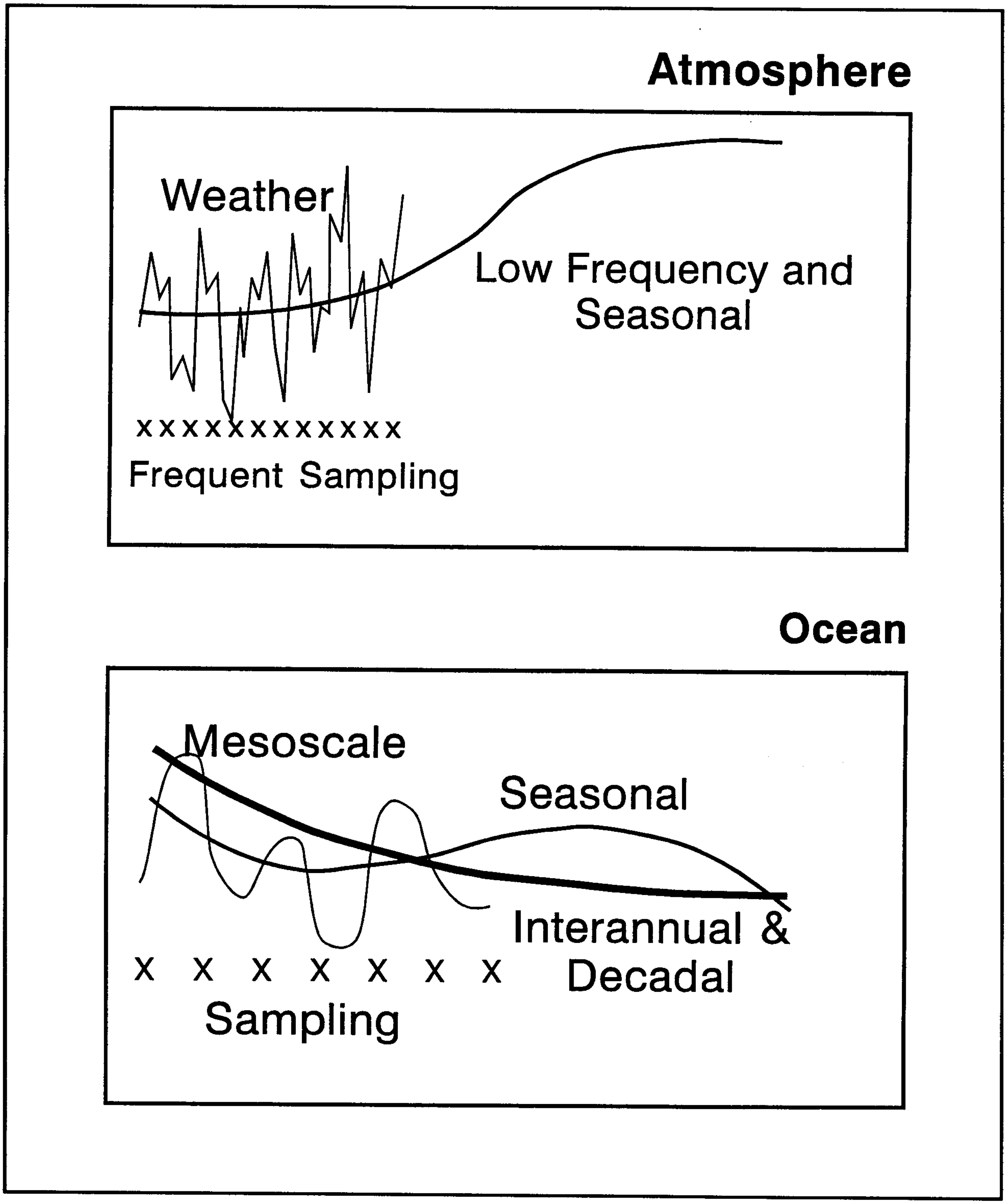



Figure IV.B.1-2. A schematic demonstrating the different sampling requirements for resolution of the seasonal (low-frequency) signal in the atmosphere and ocean in a coupled ocean-atmosphere system. The high-frequency variability in the atmosphere dictates a high sampling rate in order to avoid aliasing. In the ocean the sampling rate can be much lower because the ocean has buffered and integrated the high frequency forcing.

sampling strategy will ever be feasible so we might expect greater reliance on remote techniques such as infrared radiometers for SST and altimeters for sea surface height. In some specific regions high-resolution sampling can be used to resolve mesoscale variability (e.g., Section V.E.1).

These measurements allow indirect inference of upper ocean structure. At the scales of the subtropical gyres heat storage and transport changes on intradecadal and interdecadal scales have been documented (TOGA/WOCE XBT (eXpendable BathyThermograph probe)/XCTD (eXpendable Conductivity-Temperature-Depth probe) Programme Planning Committee (TWXXPPC), 1993). These too appear to involve ocean-atmosphere coupling and may be connected to the interannual interactions of the equatorial regions. To monitor and understand such variations it is necessary to establish a long-term, systematic upper ocean observing system with the appropriate spatial and temporal sampling resolution.

Upper ocean measurements are routinely used in three-dimensional, near-real-time analyses of the ocean and for assimilation in, and initialization of, ocean forecast models (Section I.B discussed some examples). The analysis periods tend to be of the order of a week to a month. The products from such systems are used for monitoring and understanding ocean variability on scales from weeks to decades and are now accepted as an important component of near-real-time climate analysis and diagnosis.

Net air-sea heat fluxes can also be estimated from the residuals of an upper ocean thermal data assimilation system. The surface heat flux is regarded as unknown and is inferred from the net imbalance between the modeled and analyzed thermal stratification. In some circumstances, this method of flux determination may be more accurate than direct approaches that rely on estimates using in situ, satellite, or numerical weather prediction model output. This is because there are systematic errors in calculating surface turbulent fluxes using bulk formulae. In addition, both turbulent and radiative flux determinations are affected by instrumental error, geophysical noise, and potential analysis biases (as in the case of model-based flux estimates).

On seasonal time scales and order 1000 km horizontal scales, changes in upper ocean heat storage are primarily balanced by surface fluxes over large regions of the world ocean (Gill and Niiler, 1973). Thus, if changes in heat storage can be accurately estimated, the net air-sea heat flux can be derived assuming the effects of other physical processes (e.g., horizontal advection, mixing, etc.) are small. White (TWXXPPC, 1993), for example, used XBT data from the Pacific basin to estimate changes in upper ocean heat storage for the period 1979-1991. Dividing the ocean north of 40°S into 4 large regions, he mapped upper ocean heat storage anomalies as functions of time and then estimated air-sea fluxes, seemingly resolving seasonal and interannual fluxes as small as 5 W/m$^2$.

A similar approach can be used in regions that are dynamically more complicated where advection and/or other processes may be important. Leetmaa (1993) has used a primitive equation ocean general circulation model with surface and subsurface thermal data assimilation to infer net heat flux across the air-sea interface in the tropical Pacific. The control volumes in his study spanned 5-10° of latitude, 30-40° of longitude, and 50-500 m in depth, with evaluation of heat balance terms performed weekly. Results indicated that for portions of the model domain between 30°N and 30°S, storage, advection and surface heat flux were of comparable magnitude. The inferred surface heat fluxes compared favorably with the Oberhuber (1988) climatology, and with other contemporaneous analyses overlapping the time period of the model simulations.

### IV.B.2. Scales of variability; upper ocean temperature

One of the earliest attempts to design an efficient sampling array for ocean data was by Bretherton et al. (1976) who applied objective analysis techniques to various experimental sampling array configurations using statistics inferred from the preliminary Mid Ocean Dynamics Experiment. The analysis technique was based on the Gauss-Markov Theorem which gives the least-square error linear estimate for a variable given observations at several locations and statistics in the form of space-time correlations and measurement errors. Such techniques were also the basis for many early meteorological analysis studies (e.g., Gandin, 1963).

White and Bernstein (1979) were among the first to exploit such techniques with upper ocean data in the design of an oceanographic sampling network. The North Pacific carries considerable commercial traffic. It was realized that using the XBT it would be possible to obtain regular samples in this region using commercial ships of opportunity to launch the probes. A modest program was started in 1965, and White and Bernstein (1979) analyzed the data collected between 30°N and 50°N spanning the period 1968-1974. They too used linear least-squares estimation theory and derived statistics for the mean and covariance structure of the upper ocean temperature, leading to a description of the dominant space and time scales of variability and an estimate for the noise-to-signal ratio. The data were grouped into monthly 2° latitude by 10° longitude bins. The large-scale variability had a zonal scale of 1500 km, a meridional scale of 1000 km, and a time scale of 10 months, with signal-to-noise ratio ranging from 1.5 to 0.5. They suggested that one sample per month per 200 $km^2$ would be sufficient to map the large-scale temperature to 0.2°C. Their design provided the foundation for the trans-Pacific experiment (TRANSPAC) program; recent analyses have indicated that TRANSPAC did indeed yield the information provided for by the design (TWXXPPC, 1993).

This work was extended to the equatorial Pacific by White et al. (1982, 1985). Meyers et al. (1991) later completed a more comprehensive analysis of spatial and temporal variability finding that both the scales and magnitude of the signal and noise vary with longitude and latitude and are non-stationary, being smaller in non-ENSO periods. Figure IV.B.2-1 shows the meridional scales and noise and signal levels for several regions of the equatorial Pacific (see also Table IV.A-1). The results from this study and the earlier studies of White et al. (1982, 1985) provided the foundations for the TOGA and WOCE VOS sampling designs though, as can be judged from Figure IV.B.2-1 and from the less than ideal pattern of commercial shipping, the recommended sampling rate and density and the actual implementation often differ considerably.

Similar upper ocean design studies have been carried out for the Atlantic and Indian Oceans. Bretherton et al. (1984) completed a design for VOS XBT sampling in the Atlantic for the purpose of monitoring heat content. In a more recent study Festa and Molinari (1992) completed an evaluation of the VOS network proposed for the Atlantic Ocean as part of WOCE. Like the studies discussed above their aim was to estimate the error in certain temperature fields (for example, the 400-m depth-averaged temperature) given a prescribed or actual data distribution and knowledge of the statistical properties of the field. Unlike those studies however, they preferred to use structure functions instead of covariances to represent the spatial and temporal characteristics. They estimated the errors in the 400-m depth-averaged field (for a 1° square monthly average) would be 0.3-0.4°C for the proposed WOCE design. At the time of their study, Atlantic Ocean sampling was not sufficient to produce maps with such accuracy.

Phillips et al. (1990) completed a similar study for the Indian Ocean relying upon XBT samples from several regularly occupied VOS routes. The scales of variability at the depth of the 20°C isotherm were found to be approximately 3° meridionally and two months in time with a signal-to-noise ratio near one. They concluded that the scales recommended for the Pacific Ocean (Meyers et al., 1991) would also be suitable for the Indian Ocean.

Outside the tropical regions there is notable thermal structure, at scales of order 50 km or less, associated with currents—the Subtropical Front or fronts of the Antarctic Circumpolar Current (Nowlin and Klinck, 1986), to give examples. White and Bernstein (1979) and Festa and Molinari (1992) have shown that it is feasible to map the large-scale variability of these regions, but using

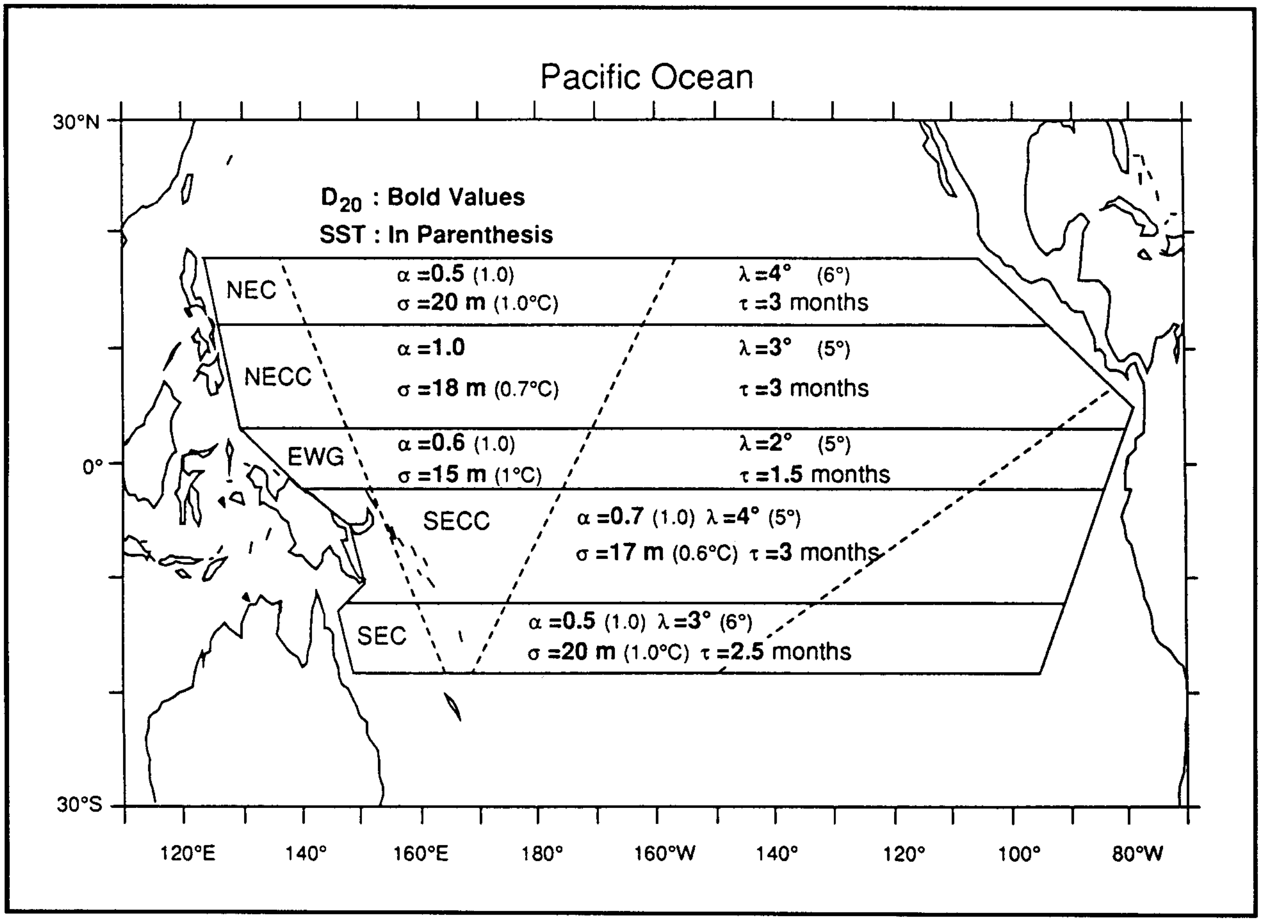



Figure IV.B.2-1. Summary of scales for optimal interpolation: signal-to-noise ratio ($\alpha$), standard deviation of measured values ($\sigma$), meridional decorrelation scale ($\lambda$), and temporal decorrelation scale ($\tau$). Values for the depth of the 20°C isotherm are in bold type; values for SST (in parenthesis) are given only if substantially different from those for isotherm depth. The sub-regions are North Equatorial Current (NEC), North Equatorial Countercurrent (NECC), Equatorial Wave Guide (EWG), South Equatorial Countercurrent (SECC), and South Equatorial Current (SEC) (from Meyers et al., 1991).

their methods fine scales such as these are part of the "noise". It is highly unlikely that any in situ ocean observing system element will be able to resolve these structures and so the observing system will look toward combinations of in situ and remote techniques (see also Sections IV.A and IV.D) plus judicious application of analysis and modeling when explicit resolution is required. Pollard and Regier (1992) provide an example of the challenges facing the observing system. They obtained density and velocity data for the top 300 m of the ocean at 4 km horizontal resolution. They found ten-fold changes in potential vorticity across a horizontal scale of 10 km in the vicinity of an ocean front, and learned that small scale (40 km) surface trapped eddies play a crucial role in the transport of properties across the thermocline and out of the mixed layer.

These problems notwithstanding there has been considerable progress in routine thermal analysis of ocean fronts and eddies, particularly for strategic applications (Clancy, 1992). These applications provide considerable insight into the vagaries of operational ocean modeling and analysis. Clancy and Pollack (1983) introduced one of the first real-time ocean thermal analysis and forecast systems using a mixed-layer model with upper ocean temperature data. This system has undergone considerable development and testing over recent years (Clancy and Sadler, 1992; Clancy, 1992). The primary focus is on nowcasting upper ocean thermal structure using optimum interpolation analysis of ship, buoy, XBT, and satellite data. They have tackled the problem of fine scales associated with fronts and major currents such as the Gulf Stream by developing ocean feature models. These use synthetic subsurface data and analyses of eddies and oceanic fronts derived from remote sensing to give a subsurface depiction of ocean mesoscale structures. The total system produces ocean thermal structure nowcasts and forecasts as well as ocean current forecasts.

For the large-scale storage and transport of heat in the upper subtropical oceans considerable progress has already been made, principally due to the regular observations taken by VOS and some repeated research surveys. The TRANSPAC data set has enabled many studies of seasonal and interannual upper ocean temperature variability, meridional heat transport and changes in the strength of the North Pacific gyre. In some cases records are sufficiently long to begin study of variability at decadal scales, though the sampling will have to be maintained for many more years before definitive conclusions can be drawn. The "Workshop on the Use of Sub-surface Thermal Data for Climate Studies" (TWXXPPC, 1993) provided several illustrations of how upper ocean data routinely gathered in the subtropics can be exploited to advance understanding of climate variability.

### IV.B.3. Scales of variability; upper ocean salinity

Dynamic variability is closely related to thermal variability in regions of the upper ocean where temperature-salinity relationships are uniform. There additional salinity data are of limited value, although documenting anomalies from the normal T-S relationship could be of interest to climate. The principal regions where upper ocean salinity variability is required are in high latitudes, where the thermal expansion coefficient is small, and in some low latitude regions where precipitation and/or evaporation rates are high (e.g., the western Pacific (Webster, 1994)). A good case can be made also for collecting salinity profiles where accurate estimates of the geostrophic current are required or where vertical mixing is critical (e.g., in the western Pacific Ocean "barrier layers" (Lukas and Lindstrom, 1987)). Understanding this "barrier layer" has been a major focus of TOGA's Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE) but, as yet, there has been no compelling evidence that knowledge of the salinity field is necessary for ENSO prediction. In the subtropics near-zonal bands of high surface salinity develop due to excess evaporation over precipitation. With evaporation beneath the trade winds this surface water is sufficiently salty to be subducted as salinity maxima at latitudes near 20° to 25°. The climatic variability of these subsurface water masses are yet to be explored. It should be remembered that although it has not been shown that upper ocean salinity in the tropics and extra-tropics plays a significant role in climate variability, this may simply reflect the present lack of skill in utilizing available information and that the sampling design should at least acknowledge the possibilities.

At high latitudes the importance of salinity is widely acknowledged, but the accrued knowledge on scales of variability is scant (see also Sections IV.A and IV.E). A cap of fresher water at the ocean surface can inhibit air-sea exchange, because the buoyancy change due to the upper ocean salt difference limits the depth of convective cooling, insulating the deeper waters from surface influence. The existence of a stable halocline in the northern North Pacific prevents that ocean from generating deep water. The North Atlantic is saltier and has a robust thermohaline circulation. This density driven flow is responsible for much of the meridional flux of water, heat, and other properties (Bryden, 1993). Paleoclimatic records indicate that deep water formation in the North Atlantic was interrupted many times, especially at the end of the last ice age (Broecker, 1987; Keigwin et al., 1991). Large amounts of glacial melt water flooded the high latitude basins, apparently causing the return to ice age conditions known as the Younger Dryas. Ocean climate models display similar variability in the thermohaline circulation (Weaver and Sarachik, 1991a, b; Maier-Reimer and Mikolwajewicz, 1989).

Evidence for such effects in recent times on smaller space and time scales has been noted by Lazier (1980) (Section II.B.2). Dickson et al. (1988) describe the "Great Salinity Anomaly", a low-salinity anomaly which could be tracked around the subpolar gyre (Sections II.B.2 and IV.A.2 and Figure IV.A.2-4).

Subsurface salinity variations on climatic time scales are less well documented than surface salinity variations. Worthington (1976) reported on variations in the extent of the salinity maximum water in the low latitude western North Atlantic; the extent appeared to be greatly diminished in a year with weak trade winds. Recently Donguy (1994) described the expansion and shoaling of the tropical Pacific subsurface salinity maximum to the west during the onset of El Niño—the region affected is a substantial portion of the basin. In the fully developed El Niño the salinity maximum moves back to the east. However, these instances are based on limited data sets, and in general we are unable to specify a sound basis for design of a sampling strategy for subsurface salinity. Our knowledge base remains at the fundamental stage as set out in Section III.C, and we must await further collection and analysis of data before scientific sampling guidelines can be laid down.

### IV.B.4. Upper ocean sampling strategies in TOGA and WOCE

TOGA and WOCE have relied substantially on two methods for routinely sampling the upper ocean temperature field: the VOS XBT program and the TOGA TAO near-equatorial mooring array in the Pacific Ocean. Research vessels, fishing and naval fleets, various other moorings, and surface and subsurface drifters provide occasional upper ocean samples, constituting an important part of the historical data set. The TOGA and WOCE programs were the first to provide systematic upper ocean sampling designs and so will be used as the primary guide for the observing system design developed here.

A summary of the TOGA XBT sampling strategy has been given by Meyers and Phillips (1992): 1) to obtain a description of the large-scale thermal structure, 2) to obtain the data for testing and verification of tropical ocean models, and 3) to provide timely data for ocean data assimilation systems. The goals of WOCE for upper ocean temperature (WCRP, 1988a) are 1) to measure changes in the heat content of the upper ocean on basin scales, 2) to estimate the statistics of the thermal field in the upper 1000 m and 3) to observe variations of the zonal and meridional fluxes of heat on time scales of seasons to years. The TOGA goals are principally aimed at developing and initializing tropical ocean and coupled atmosphere-ocean models while WOCE places more emphasis on monitoring, understanding and describing the global upper ocean.

The upper ocean sampling designs developed for the TOGA and WOCE programs employ two different strategies.

1) The low-density or broadcast mode sampling strategy is aimed principally at determining the monthly to interannual variability in the large-scale upper ocean heat content, and the mechanisms underlying its variation. The guideline set for TOGA indicated a reasonable level of accuracy could be achieved with one XBT station every two months for each 1.5° latitude and 7.5° longitude. Smith et al. (1991), Meyers et al. (1991), Festa and Molinari (1992), and recent experience (e.g., TWXXPPC, 1993) suggest the actual error averaged over the tropical Pacific is 0.5-0.7°C. This strategy has under-pinned much of the sampling in the tropical Pacific Ocean undertaken for the TOGA program and has provided the basis for improving our fundamental knowledge of the tropical ocean heat budget as well as providing essential data for validation and initialization of ocean models. WOCE is supplementing the coverage provided by TOGA in the tropics and other programs elsewhere as well as initiating new surveys in regions like the South Atlantic and southern Indian Ocean. In the Atlantic, the WOCE objective is for a coverage similar to that which

TOGA achieves in the tropical Pacific, though slightly reduced (Festa and Molinari, 1992). Some XBT sections (e.g., TRANSPAC) have been repeated over several decades and thus provide important long-term monitoring of the climate system.

2) High-density spatial sampling on selected lines is used to determine the spatial variability and structure of the temperature and geostrophic current fields at mid and high latitudes and to measure low-frequency changes in the large-scale circulation and transport, including circulation associated with smaller scale features such as coastal boundary currents and fronts. The high-density mode is to provide data at around 50 km resolution. This strategy is being adopted in WOCE with the emphasis on geostrophic currents and transports associated with fronts, mesoscale eddies and boundary currents. For both the low and high density modes WOCE has additionally recommended the use of XCTDs in selected regions. An example of the use of a high-density section is given in Figure IV.B.4-1 which compares geostrophic transport calculations based on repeated high-density sampling in the South Pacific (Roemmich and Cornuelle, 1990) with an estimate derived from a single WOCE hydrographic section. Roemmich and Cornuelle (1993) conclude that spatial resolution can be sacrificed through judicious smoothing in order to obtain a higher degree of representativeness of a single realization (in this case the WOCE hydrographic section). They point out that a detailed knowledge of the statistics of ocean variability is required for such a tradeoff.

An example of this latter strategy is given by the frequently repeated transequatorial sections, carried out by TOGA, aimed at well resolved time series of heat storage and geostrophic transports of major currents in the equatorial circulation systems. Using such sections it is possible to resolve transports due to narrow equatorial current systems such as those in the equatorial Pacific Ocean and in the Indian Ocean in the vicinity of the Pacific-Indian throughflow (e.g., Meyers et al., 1994).

The sampling objectives of the observing system for upper ocean temperature and salinity, as far as they can be articulated at this interim stage, follow TOGA for the tropical region and WOCE for the subtropics and mid-latitudes. The observing system will rely on further research within these programs to help refine this strategy and to begin the difficult task of quantifying contributions to these objectives from different data types.

## IV.C. Velocities

The wind stress directly drives ocean surface currents, and the fluxes of heat and fresh water across the air sea interface provide non-uniform buoyancy forcing. The large-scale convergences and divergences of the wind-driven currents coupled with the buoyancy forcing drives the large-scale, three-dimensional circulation in the ocean interior and its associated mass field. To the first order, the velocity field (except at the equator) is in geostrophic adjustment with the mass field at time scales longer than that of the tides and inertial motions. At such time scales and away from the major boundary and equatorial current systems, where it has been measured the variability of the velocity field in the deep ocean is usually greater than the mean, when averaged over periods of a year or so. This is as much a result of the instabilities in the circulation as from variability in the surface forcing. Measures of this meso-scale activity and its modal structure are of importance in the verification of ocean models.

An idea of the wide variety of the space and time scales of the oceanic velocity field near the surface may be seen in infrared measurements of the sea surface temperature. It shows variability associated with major surface currents, including the western boundary currents such as the Gulf Stream and the equatorial current systems. Some of this has scales of less than 100 km. Mesoscale variability is seen at ocean fronts and, in some locations, is forced directly by the atmosphere. Oceanic dynamics give rise to small scale structures with longer persistence times than is associated

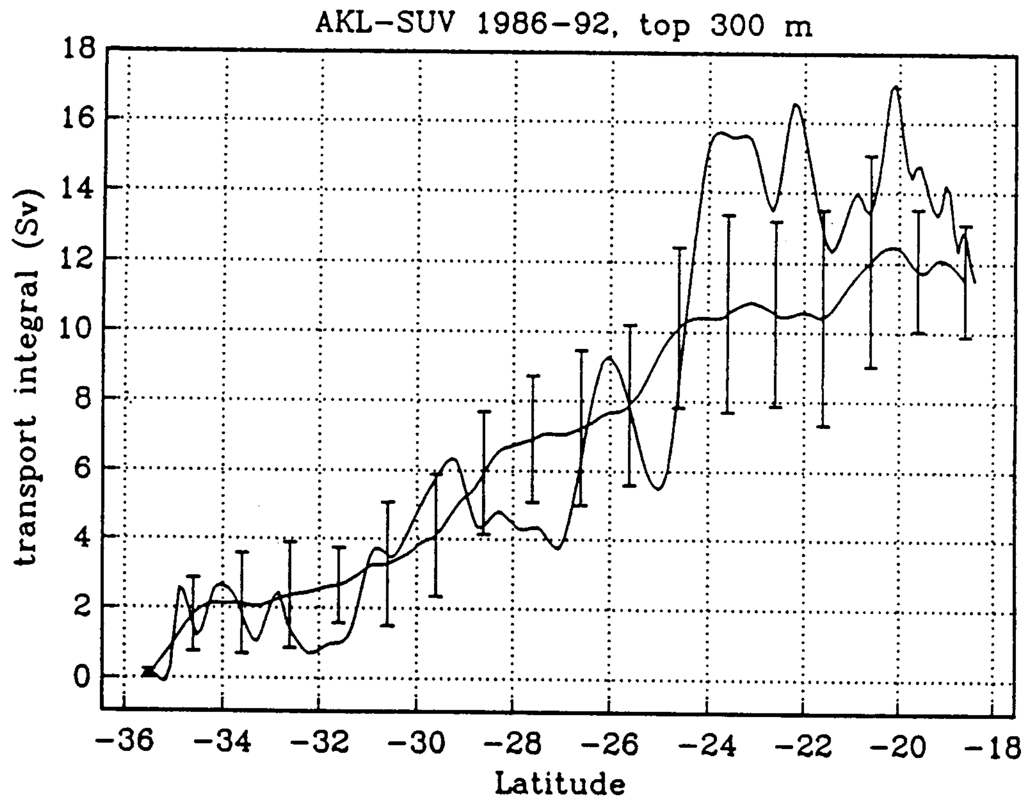



Figure IV.B.4-1. Mean (smooth solid line) and standard deviation (bars) of geostrophic transport in the upper 300 m relative to 800 m, as a function of latitude, integrating northward along the Auckland-Suva high-density VOS XBT line. The second solid line is the corresponding transport integral for the WOCE Hydrographic Program leg P14C using 52 full depth CTD/hydrographic stations. (From Roemmich and Cornuelle, 1993.)

with such scales in the atmosphere. Ocean fronts, often with strong current systems and typical widths of 10 to 50 km, are found in many situations such as at the location of major atmospheric convergences, in association with shoaling bottom topography and at the edge of strong boundary currents. Jets of cool, upwelled water between 10 and 40 km in width and 4°C cooler than surrounding waters have been reported in several areas: for example, off California (Rienecker and Mooers, 1989) and Namibia (Shillington et al., 1990). The mean energy in surface currents as observed by ship drift provides another measure of the spatial variability of mesoscale currents. For more information regarding the space and time scales of surface currents see Section IV.A.

At the equator, zonal scales in the ocean are larger, reaching the width of the ocean basins, and the velocity field is dominated by a series of strong currents and countercurrents both vertically and meridionally. The temperature signature at the surface and in upper ocean of these current systems and various equatorial waves that propagate along the equator has been discussed in Sections IV.A and IV.B. A limited number of direct current measurements have been made in these regions, usually as a contribution to more complete field programs, and confirm many of the same features. For example, Weisberg et al. (1979) found oscillations with a period of 31 days and wavelength of 1200 km in deep current meter records in the eastern Atlantic; Weisberg and Horrigan (1981) showed that these oscillations are associated with waves whose source is at the surface in the central Atlantic and which are seasonally modulated. Weisberg and Weingartner's (1988) subsequent analysis of surface currents shows a wave with 25-day period, 1140-km wavelength, and westward phase propagation of 0.5 m/s at 15°W in the equatorial Atlantic. Reverdin and Luyten (1986) have found similar waves in the western equatorial Indian Ocean.

Satellite altimeters have provided global information on ocean currents and their variability not previously available. This is improving with results from the altimeters on ERS-1 and TOPEX/POSEIDON (see Figure II.A-1 from Tapley and Shum, personal communication). Although away from the equator sea surface elevation is an expression of the surface quasi-geostrophic current field, its interpretation in terms of deep mesoscale currents requires knowledge of the vertical modal structure obtained by other means. Energetic mesoscale sea surface variability, with scales of hundreds of kilometers, is present in most locations in the ocean with a tendency for the open ocean scale to get smaller as the Rossby radius of deformation decreases from the equator to the poles. The global variation of the energy of mesoscale motions has been analyzed by Fu and Zlotnicki (1989) and Zlotnicki et al. (1989) who used Geosat altimeter data to examine temporal signals in mesoscale sea level variability on a global basis. The largest variances were found associated with the strong boundary currents (the Agulhas Current south of Africa, the Kuroshio off Japan, the Gulf Stream off the east coast of North America, the East Australia Current, and the Falkland Current) and the Antarctic Circumpolar Current. Seasonal change was found in many locations. In equatorial regions, factors other than oceanic variability, such as migration of the ITCZ that changes the water vapor content of the atmosphere and thus affects the altimetric data, may introduce non-oceanic seasonal variability in the altimeter. In the northeast Pacific and in the northeast Atlantic, however, Zlotnicki et al. (1989) believe the seasonal signal in the altimeter data reflects seasonal variability in the mesoscale flow field in the ocean. Wunsch (1991a, b) combined altimetric and tide-gauge data to obtain the variability at larger (basin) scales (see also Section IV.D).

A number of analyses of altimeter data have provided regional estimates of space and time scales. Wavenumber spectra of the sea surface elevation from Geosat altimeter data for the North Atlantic (Le Traon et al., 1990; Stammer and Böning, 1992) show a well-defined red region over wavelengths of roughly 50 km to 200-500 km depending on the location, a plateau in the spectra at longer wavelengths (200 to 1000 km), and an indication of a drop in energy at the longest scales (1000 to 2000 km). At the dominant scales the period was found to be greater than 150 days in the eastern Atlantic but near the Gulf Stream significant energy was found at shorter periods (e.g., Le Traon, 1991). Seasonal variability of the Gulf Stream has also been seen in altimeter records (Fu et al., 1987). Off Japan, in the extension of the Kuroshio, Tai and White's (1990) examination of Geosat altimeter data found peaks in wavenumber frequency spectra at 500 to 1000 km zonal wavelengths and periods of 170 to 240 days. They also report a seasonal cycle in the strength of the eddy field, with the least energetic period in the winter. Kindle and Thompson's (1989) model of the western Indian Ocean shows strong eddy variability (approximately 250-km radius) along the eastern coast of Africa near the equator.

Direct measurements of the large-scale velocity field and its variability in the interior of the ocean are possible using both moored current meters and deep floats. Both techniques have been used to measure the circulation but this has usually been in a limited region and for a particular research interest. The first use of floats on a global scale is being conducted by WOCE with the goal of obtaining about five years of float data per 500 km square. For WOCE, floats are being released between about 1000 and 2000 meters in an attempt to measure the slow deep circulation to an accuracy not possible using a combination hydrography and the sea-surface elevation. A review of the use of floats and the analysis and interpretation of the Lagrangian measurements obtained has recently been given by Davis (1991). The largest historical float data set exists for the western North Atlantic. Owens (1991) has analyzed some 230 float trajectories and 240 float years of data from various depths up to 2000 meters that have been collected over the last 20 years. He shows that the data set is extensive enough to define the Gulf Stream east of Cape Hatteras, the formation of the North Atlantic Current, and a southward recirculation. In general, it is found that the eddy kinetic energy is greater than the mean kinetic energy and that both decrease with depth in a manner consistent with current meter mooring records from the region.

Current meter moorings have been used in arrays, sometimes coherent in their spacing, for the purpose of investigating and monitoring the flow in major ocean current systems, including western boundary currents such as the Gulf Stream (Hendry, 1982) and Kuroshio (Pillsbury et al., 1985), the Antarctic Circumpolar Current at Drake Passage (Nowlin et al., 1981), and flow through passages such Denmark Strait (Dickson et al., 1990). They have also been used to explore the statistics and vertical structure of currents in the open ocean (Schmitz, 1978; Schmitz et al., 1987). During WOCE many of the major current systems, including some that have not previously been investigated, will be measured, usually for a period of about two years that in many regions is about the minimum period over which the mean may be reasonably estimated.

Using all the direct current measurements available in 1981 in the international research community, Dickson (1983) prepared a global summary of the statistics (mean and eddy kinetic energy) of deep ocean currents. As a contribution to WOCE, Dickson traveled worldwide in 1988 collecting newer records and has compiled an updated climatology (Dickson, 1989). Many of the longer records are from the depth interval 3800 to 4300 m and these have been used by a number of investigators as a basis for comparison of current statistics. Another concentration of records, many from the tropics, comes from nearer the surface between 0 and 800 meters. Dickson finds the largest kinetic energies in the flow under or near the Gulf Stream and Kuroshio but notes differences as well as similarities in the deep currents in the North Atlantic and Pacific oceans which are the source of most records. This climatology provides basic information about ocean currents and their variability that must by taken into account by climate modelers.

## IV.D. Sea Level

The topography of the sea-surface relative to Earth's geoid is a basic measurement of the oceanic response to forcing allowing for estimation of the geostrophic current and its variability. Indeed, satellite altimetry now provides the only truly global, near-instantaneous measurement of the ocean's large-scale circulation and its variability. Specially processed altimetry measurements can even provide estimates of geostrophic zonal flow at the equator (Picaut et al., 1990). Thus altimetric measurements are key to describing and modeling the ocean circulation. Thus, they are essential to global climate research programs such as WOCE and will be required as a part of the ocean observing system for climate. Tide gauges presently provide the only records of long-term sea level temporal variability and can be of high accuracy.

Koblinsky et al. (1992a) discuss the goals of altimetric missions and the many oceanographic phenomena that might be resolved with such data (see Table IV.D-1 from Koblinsky et al. with additions for the Antarctic Circumpolar Current and mid-ocean fronts). The phenomena include sea state, eddies, boundary currents, fronts, gyres, and basin-scale sea level change (e.g., ENSO). Altimeters can measure sea-level changes on a broad space and time scales; determination of absolute geostrophic velocities depends on better knowledge of the marine geoid, especially on space scales of less than 2000 km (Koblinsky et al., 1992a). Special geodetic satellite missions, which would improve knowledge of the marine geoid, have been proposed and remain a requirement. There is also a need for a high-quality global tide-gauge network of order 50 gauges for calibration and validation of sea-level elevation measurements obtained from satellite altimeters.

| Phenomena | Vertical Range (cm) | Spatial Scale (km) | Time Period (days) |
|---|---|---|---|
| Ocean Gyres | | | |
| — Means | 100 | >1000 | |
| — Variations | 10 | >1000 | >300 |
| Mesoscale Eddies | 25 | ~50 | >30 |
| Western Boundary Currents | | | |
| — Mean | 100 | 100 | |
| — Meanders, Variations | 100 | 100 | >10 |
| Eastern Boundary Currents | | | |
| — Mean | 20 | 500 | |
| — Meanders, Variations | 10 | 500 | >10 |
| Equatorial Currents | | | |
| — Mean | 20 | >500 | |
| — Meanders, Variations | 10 | >500 | >50 |
| Cores of the Antarctic Circumpolar Current | 25 | 50 | >50 |
| El Niño Response of Equatorial Sea-level | 20 | >500 | ~1000 |
| Mid-Ocean Fronts | 10 | 10 | ~10 |

Table IV.D-1. Typical sea level variations associated with various oceanic phenomena (from Koblinsky et al., 1992a, with additions for the Antarctic Circumpolar Current and mid-ocean fronts).

This requirement for tide gauges may be reduced as experience is gained with precision satellite altimeters such as TOPEX/POSEIDON. Most of the information on sea level variability obtained from altimeters that is referenced in this document is based on Geosat data. The altimeter data obtained from ERS-1 launched in 1991 and, especially, from the next generation altimeter on TOPEX/POSEIDON launched in 1992 are now being analyzed and are rapidly providing evidence of the accuracy to which sea level variability on all space-time scales can be measured from space.

Altimetric measurements from experimental satellites have been shown to provide good estimates of the global variations of sea level and constitute the only means for gathering global information on the ocean circulation, its large scale variability and its response to surface forcing (Wunsch, 1991a, b). Altimetric measurements produced the first maps of global mesoscale variability and of the ocean circulation (Koblinsky et al., 1992a; Cheney and Marsh, 1981). Recent analyses are revealing a great deal about the variability of, for example, the Agulhas Current (Gordon and Haxby, 1990) and of variability in the Southern Ocean (Chelton et al., 1990). These analyses make use of satellite track cross-over points to reduce geoid and radial orbit errors. In Section IV.C, some altimeter based analyses of the space and time scales of mesoscale variability have also been discussed.

Altimetry will be used to tie together the spatially and temporally scattered observations of an observing system. Consider Figure IV.D-1 from Wunsch (1991a). It shows the three-month average variability from a two-year average of the sea-surface of the global ocean as derived from Geosat data combined with a global network of tide gauge data contemporaneous with the altimeter mission (see also Koblinsky et al., 1992b). Using data from the Geosat mission, the results were confined to long wavelength components (longer than 4000 km) averaged over a rather long period. Nonetheless, within the context of the accuracy and precision of the combined data sets, the observed large-scale, low- frequency changes in sea level were shown to be correlated with the surface atmospheric forcing as defined by the sea surface pressure and its gradients. Wunsch (1991a, b) discusses its accuracy and precision. (Subsequently, some Indian Ocean tide gauge records became available; the figures depicted are completely consistent with those independent data.)

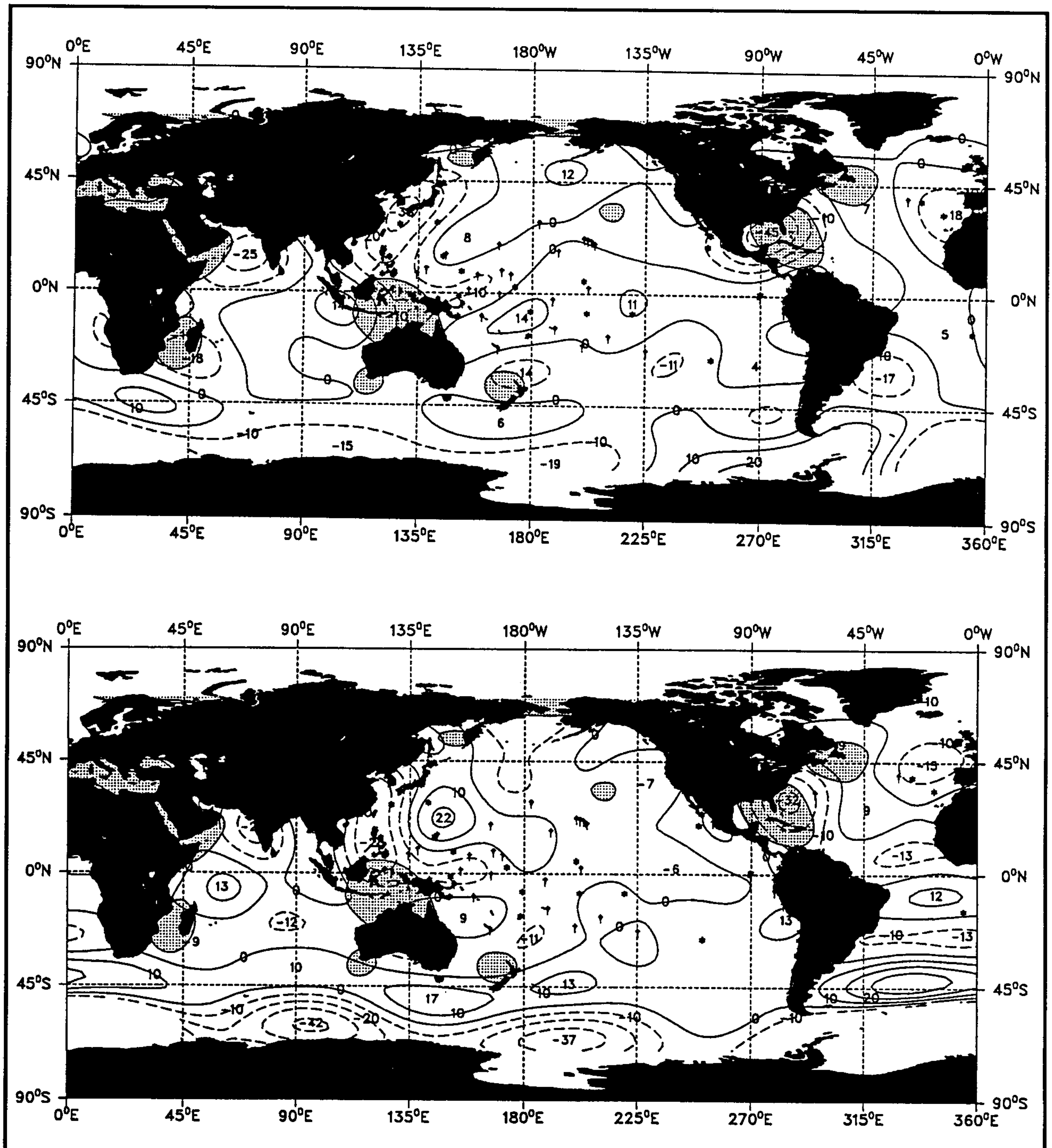



Figure IV.D-1. (upper) Long-wavelength sea level change relative to the two-year mean for the period August 11, 1986 to July 17, 1987. Geosat altimetry and tide gauge data were used and the spherical harmonic expansion runs to degree and order 10. Category 1 gauges (indicated by †) have records from which a two-year average could be computed and subtracted; category 2 gauges (indicated by *) had records which were too fragmented to compute a useful average and were used in a different manner. Units are centimeters; contour interval is 10 cm. Regions of expected error exceeding 4.5 cm are shaded. (lower) Same as for (upper) except February 18, 1987 to May 3, 1987 (from Wunsch, 1991a).

Sea level elevation at the equator is, to first order, correlated with the displacement of the main thermocline and thus should provide an integral measure of the heat content. In situ measurements of sea level from tide gauges have been demonstrated to have utility for the detection of the ENSO signal (Wyrtki, 1979). For example, Wyrtki (1984) used Pacific Ocean island tide gauge data to map the sea level response during the 1972 ENSO. Meyers (1982) was able to demonstrate the bimodality of the ENSO signal by analyzing historical sea level records. The scales of spatial variability resolved by the in situ network are limited by the availability of suitable tide gauge sites. The long zonal scales, and the associated time scales of propagation, of the sea level response during ENSO enable the monthly mean data to be used as a monitor of such variability. These data are made available in near-real- time by the sea level center at Hawaii (Wyrtki et al., 1988).

WOCE has strategically placed tide gauges to measure the flow through selected passages, e.g., south of South America, Africa, and Australia to monitor the Antarctic Circumpolar Current. However, the interpretation of the signal from such pairs is often difficult and requires some sort of local "calibration". The alternate technique of using cables to monitor flow through passages, which also requires calibration, may be superior at some locations and preferred for an observing system.

Although tide gauges have for the most part been put in place to obtain information on local conditions, they can provide relatively long records for climate studies when other ocean data does not exist. Thompson (1986) analyzed records from tide gauges around the North Atlantic and found that along the eastern boundary there is a significant relationship between sea level and the large-scale Ekman pumping over the ocean basin. Along the western boundary, although sea- level is coherent along the coast north and south of Cape Hatteras its variability cannot be related to off-shore phenomena. Sturges (1987) examined long tide gauge records from Honolulu and San Francisco in the Pacific and found indications of Rossby wave propagation in the coherence of the records in the frequency band of five to eight years, with a phase lag of several years. He also found evidence of fluctuations with periods of 40 to 50 years, which are coherent between the Atlantic and Pacific. Roemmich (1990) compared 27 years of repeated deep hydrographic station data from the Panuliris Station near Bermuda with tide gauge records also at Bermuda. He found decadal time scale variations in the full depth temperature record and a corresponding change in the steric height which is closely followed by observed sea level changes in the tide gauge record at Bermuda.

Tide gauge records have also been used to delineate the long-term signal that may be related to climate change (for a summary see IPCC, 1990). Barnett (1983b, 1984) analyzed long tide gauge records over the period from 1880 and found a global average sea level rise of 1.5 to 2.00 mm/yr with the rate being greater than the overall average in the period since about 1930. The interpretation of this sea level rise in terms of global climate change is complicated by the fact that the local sea level is affected by glacial isostatic disequilibrium. This effect can be estimated by the use of geophysical models of the deglaciation-induced relative sea-level change (Peltier and Tushingham, 1989). The expected change in sea level from oceanic thermal expansion alone as a result of global greenhouse gas warming is estimated to be 2-4 cm/decade at the time of the doubling of greenhouse gases (IPCC, 1992). However, this sea level change will not be spatially uniform because the steric adjustment due to thermal expansion will be uneven (driven by the change in ocean temperature) and the sea level will also adjust to changes in oceanic circulation (Gregory, 1993).

## IV.E. Heat and Freshwater Transports

### IV.E.1. Ocean heat transports; scales of variability

The radiation budget of Earth is characterized by strong input of solar energy at low latitudes and a back radiation to space that is more evenly distributed over the globe (Figure IV.E.1-1). This sets

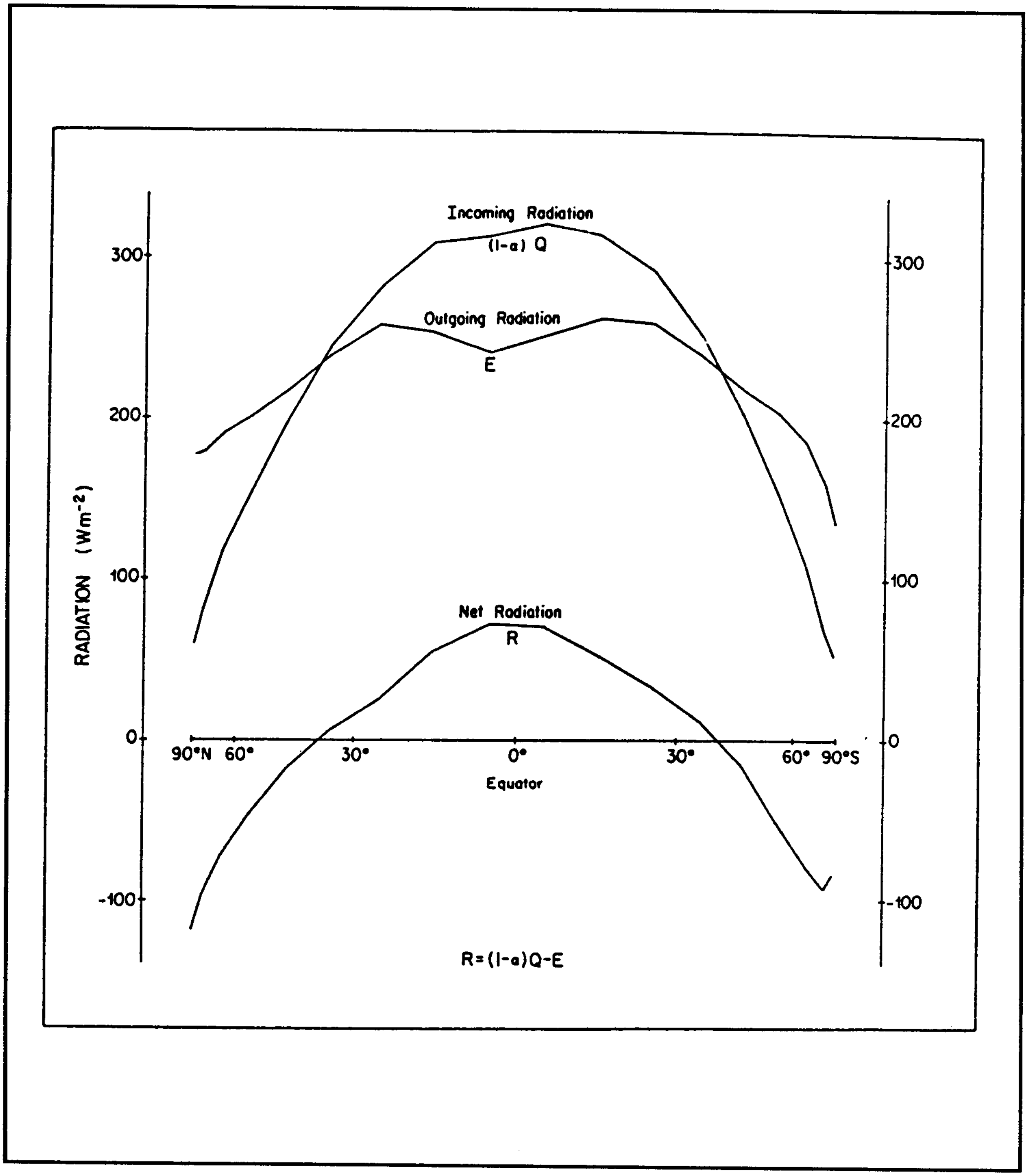



Figure IV.E.1-1. Annual-averaged radiation at the top of the atmosphere (derived from tables in Stephens et al., 1981). Net incoming short-wave radiation, (1-$\alpha$) Q, where Q is incoming radiation and $\alpha$ is the albedo, is concentrated in the tropical regions. Outgoing long-wave radiation, E, is somewhat more uniform with latitude. The net incoming radiation, R=(1-$\alpha$) Q-E, then is positive for latitudes equatorward of about 35° and negative for latitudes poleward of 35°. A uniform bias in net incoming radiation of 9 W/m$^2$ has been subtracted to ensure radiation balance over the globe (from Bryden, 1993).

the global scale of variability in oceanic heat flux. The difference between incoming short wave radiation and net outgoing longwave radiation at any location determines the necessity for divergence in the heat flux carried by the ocean and atmosphere, since on an annual basis the trend in temperature should be very small (reflecting only long-term climate trends). This implies a net poleward transport by the ocean and atmosphere. Satellite radiation measurements at the top of the atmosphere by Stephens et al., (1981) indicate that up to 5.5 Petawatts (PW) (1 PW=$10^{15}$ watts) must be transported poleward in mid-latitudes (35°) in both hemispheres.

The apportionment of this heat flux between ocean and atmosphere has been a matter of some controversy. As noted by Bryden (1993) meteorologists have tended to ascribe a greater role in meridional heat transport to the ocean than have oceanographers (Vonder Haar and Oort, 1973; Oort and Vonder Haar, 1976; Oort and Peixoto, 1983; Carissimo et al., 1985). These inferences are based on estimates of the atmospheric heat transport, which are then subtracted from the satellite derived radiation budget to yield the ocean heat transport as a function of latitude (Figure IV.E.1-2). Such calculations require nearly 4 PW of poleward heat transport by the ocean in mid-latitudes. On the other hand, integrations of surface ocean heat fluxes derived from bulk formulae by Budyko (1974) and Talley (1984) find less heat transport by the oceans, typically 1 to 2 PW in mid-latitudes. Of course there are uncertainties in the radiation budget due to bias corrections, in the meteorological budgets due to the lack of data over the oceans, and in the ocean surface flux estimates due to lack of data and errors in the bulk formulae.

At 24°N Bryden (1993) has combined data from Atlantic and Pacific sections in order to calculate the total ocean heat transport directly. He finds that the sum of ocean heat flux estimates is 2.0 PW, with 1.2 PW in the Atlantic, 0.8 PW in the Pacific. The uncertainty is estimated to be at most 0.45 PW, too small to explain much of the disagreement with the radiation and meteorological measurements, which is up to 1.5 PW. Since even an extra 1 PW would require the discovery of another Gulf Stream system, it seems unlikely that much of the discrepancy can be attributed to the ocean. Some have speculated that unresolved atmospheric water vapor transport over the ocean may account for the discrepancy. However, this can be constrained by the ocean water budget estimates, since the ocean is the main return path for water carried by the atmosphere. As discussed later, the ocean data at 24°N do not support an increase in the latent heat flux. Thus, we must look to recalculation of the atmospheric transport (Trenberth and Solomon, 1994) or the radiation budget (Gilman and Garrett, 1994) to resolve the discrepancy. Indeed, numerical weather models, with better resolution of eddy heat fluxes, yield greater estimates of the atmospheric heat transports (Masuda, 1988; Michaud and Derome, 1991).

While there are uncertainties in the amplitude of ocean heat fluxes, the general pattern of meridional fluxes is revealed by either the residual of the radiation and atmospheric estimates or the integrations of the surface fluxes. These show that there is near zero net heat flux across the equator, and mid-latitude maxima in poleward transport. While there is uncertainty in the data, Figure IV.E.1-2 suggests that ocean heat transports in the southern hemisphere may be less than those in the north. The pattern of heat transports in the individual ocean basins differs substantially from the global zonal average. For example, in the South Atlantic there is an equatorward heat flux (Stommel, 1980; Rintoul, 1991) as a result of the strong heat loss in the high latitude North Atlantic associated with bottom water formation and the global thermohaline convection cell. Since the Pacific is believed to have little or no cross-equatorial heat flux and since the net ocean heat flux across the equator is small, the northward flux in the Atlantic must be compensated by a southward flux across the equator in the Indian Ocean.

The direct ocean heat flux estimates (Hall and Bryden, 1982; Bryden et al., 1991; Wunsch et al., 1983; Rintoul, 1991) are of great value for constraining the planetary heat budget. They reveal the mechanisms of ocean heat transport. Hall and Bryden (1982) found that it is a deep meridional circulation cell which carries the heat flux in the Atlantic at 24°N. About 18 Sv of water warmer

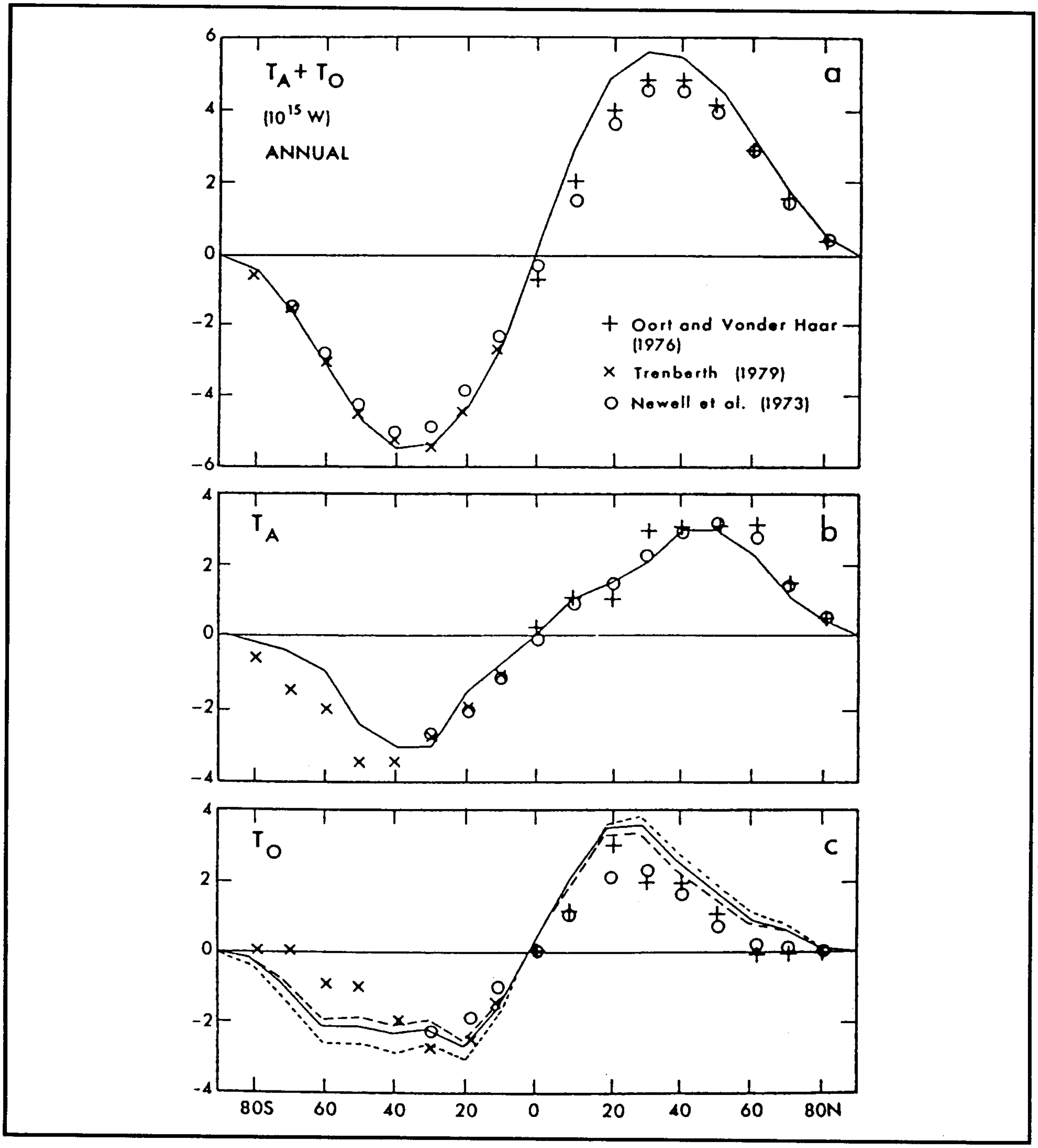



Figure IV.E.1-2. Annual transport of heat (Carrisimo et al., 1985, Figure 4): (upper) total atmosphere + ocean energy transport determined from satellite radiation measurements in Figure 1 (Stephens et al., 1981); (middle) atmospheric transport determined from analysis of the rawinsonde network (Carissimo et al., 1985); and (lower) oceanic transport determined as a residual between (upper) and (middle). In (lower) the three curves for oceanic transport are based on different bias corrections to the satellite radiation measurements. Results obtained by some previous investigators are added for comparison (from Bryden, 1993).

than 12°C flows northward and a similar amount colder than 4°C returns southward. Surprisingly, the horizontal cell of the Gulf Stream and its interior return flow actually make a small negative contribution to the heat flux, since the water deeper than 200 m in the Gulf Stream is slightly cooler than interior waters at the same depth.

A quite different picture emerges in the North Pacific. There the horizontal cell shallower than 800 m contributes half the heat flux at 24°N (~0.4 PW of 0.8 PW) (Bryden et al., 1991). The other half is given by a shallow vertical cell associated with the wind driven Ekman transport. Only very small deep water mass modifications are observed in the Pacific and these make a negligible contribution to the meridional heat flux. It is thought that the Pacific produces no deep water because the surface waters are relatively cold, which reduces evaporation, allowing precipitation and fresh water runoff to produce a fresh stable upper ocean (Warren, 1983). Conversely the Atlantic experiences greater evaporation (Schmitt et al., 1989) and the inflow of high salinity Mediterranean water (Reid, 1979) and thus has high enough salt content to generate bottom water. However, no coupled ocean-atmosphere model can yet model such differences in driving and response of the two oceans. Indeed, current climate models employ "flux corrections" in order to keep sea temperatures within observed bounds.

In the Southern Hemisphere, the net ocean heat transport appears to be much smaller than in the north. Because of its strong thermohaline circulation, the heat transport at 30°S in the Atlantic is actually equatorward, and is about 0.5 PW. Estimates of mid-latitude heat fluxes in the South Pacific are small (Wunsch et al., 1983), despite its great size (about 0.5 PW southward). However, Toole and Warren (1993) have recently described a rather robust overturning cell in the South Indian ocean which transports about 1 PW to the south. As summarized by Toole (1993), the mid-latitude southern hemisphere ocean is estimated to transport about half the heat flux of the northern ocean, consistent with the sense of the differences seen in Figure IV.E.1-2.

Planned and on-going zonal sections of the WOCE Hydrographic Programme will provide a much improved picture of the global ocean heat fluxes. However, little is known on the representativeness of such one-time sections. One section, at 24°N in the Atlantic, has been repeated three times, in 1957, in 1981 and in 1993. Significant differences in the temperatures of deep and intermediate waters have appeared in these sections over the one to three decades separating the occupations. The trend is a warming of the deep and intermediate water. However, the heat flux calculated from these sections has been found to be the same. Since the Atlantic heat fluxes are strongly dominated by the meridional overturning cell, especially at 24°N, this probably reflects the stability of the thermohaline conveyor belt on decadal time scales. At other latitudes and in other ocean basins, such stability should not be expected, as the wind driven circulations, as well as eddy transports, play a more important role in the heat flux. Analysis of the WOCE sections will provide an important first order picture of the latitudinal distribution of heat and freshwater fluxes, useful for defining the scales and patterns of variation.

### IV.E.2. Ocean freshwater cycle; description

The hydrologic cycle is a key component of the climate system. Yet we are remarkably ignorant about ocean freshwater transports, even though the oceans are the main return path for water carried in the atmosphere. Freshwater inputs to the ocean can influence air-sea exchange by affecting the upper ocean salinity profile. The resulting stratification changes may modulate ENSO at low latitudes and the thermohaline circulation at high latitudes (Section IV.B). Measurements of the ocean water budget provide useful constraints on the latent heat flux. Improved time series of hydrologic forcing parameters are required to monitor changes in the patterns of precipitation over the sea, which may result from greenhouse warming. In the following, major issues and scales of variability for the ocean freshwater fluxes and salt distributions are discussed within the context of the observing system. We focus on those items of particular importance to the ocean hydrologic cycle that are not presently well measured. (That is, we do not discuss river flows, which are generally monitored to higher accuracy than other components of the hydrologic cycle.)

To model the dynamics and thermodynamics of the ocean climate system it is necessary to determine the surface buoyancy flux. In many areas the contribution of evaporation and precipitation to the buoyancy flux may exceed that of the thermal transfer. Schmitt et al. (1989) use available evaporation and precipitation climatologies to show that in significant portions of the North Atlantic subtropical gyre the buoyancy fluxes are dominated by the freshwater flux. One way of considering this is to examine the absolute value of the thermal/haline density flux ratio for which values near unity indicate that heat and freshwater fluxes make nearly equal contributions to the buoyancy fluxes. K. Speer (Willebrand, 1993) has utilized an alternative evaporation data set and finds that even more of the subtropical gyre has a freshwater buoyancy flux well in excess of the thermal flux (Figure IV.E.2-1). Both data sets suggest that hydrologic forcing is relatively less significant in the open ocean of the subpolar gyre; run-off and ice melt may be more important high latitude buoyancy sources. The importance of the freshwater to the buoyancy flux, and the large uncertainty in its magnitude, demands that a great improvement in quantification of the ocean hydrologic cycle be achieved if climate models are to be improved.

In addition to monitoring the buoyancy changes caused by surface freshwater forcing, it is important to account for the mass flux. Ocean currents transport many times as much water as the atmospheric branch of the hydrologic cycle. The surface flux itself drives the Goldsborough circulation (Huang and Schmitt, 1992), which, though small, is often in opposition to the wind driven flow, and may affect the separation latitude of western boundary currents. The net differences in evaporation minus precipitation (E-P) between basins help to drive interbasin transport. A prime example is the flow through the Bering Strait, which returns most of the excess precipitation received over the fresh North Pacific to the salty, evaporation-dominated Atlantic. It is important to determine such interbasin transports since they define the net water and salt fluxes carried across coast to coast ocean sections. As Wijffels et al. (1992) point out, the fluxes of salt and water must be separately treated. While it may be useful in regional studies to examine positive or negative freshwater anomalies away from a reference salinity, such an approach cannot be extended to a global scale because there is no universal reference salinity. Indeed, the average salinity of the ocean must have varied with the changing ice volume during glacial periods. The Wijffels et al. (1992) scheme using the estimated Bering Strait transport (Coachman and Aagaard, 1988) as an integration constant yields a global ocean transport scheme that contrasts dramatically with earlier work, which arbitrarily assumed no net water transport across the Atlantic equator. (Figure IV.E.2-2).

The flow of water and salt from the Pacific to the Arctic and Atlantic through the Bering Strait is driven by a slight elevation of the Pacific relative to the other oceans. Estimated to be some 50-60 cm, it is caused by the lower salinity of the Pacific. The North Pacific is more diluted by rainfall than the Atlantic. Nearly all the excess water falling on the North Pacific exits through Bering Strait, carrying with it a fair bit of salt. The salt transport through the Bering Strait must be resupplied by oceanic flows in the tropical Pacific through the northward flow of salty water and the southward flow of fresher water. Similar mass- and salt-compensating flows are predicted for the South Atlantic, which must export the salt gained through Bering Strait but need export little water, because the surplus fresh water coming from the Pacific and high latitude runoff and rainfall has been lost by evaporation in the subtropical and tropical Atlantic.

This appreciation of the separate nature of water and salt transports in the ocean is leading to new insight into the importance of ocean data in constraining the global hydrologic cycle. From zonal hydrographic sections across an ocean basin it is possible to estimate the salt and net water flows if the interbasin transport is known. For instance, if the flow of water through Bering Strait were not matched by southward water transport in the North Atlantic, North Atlantic sea level would rise by

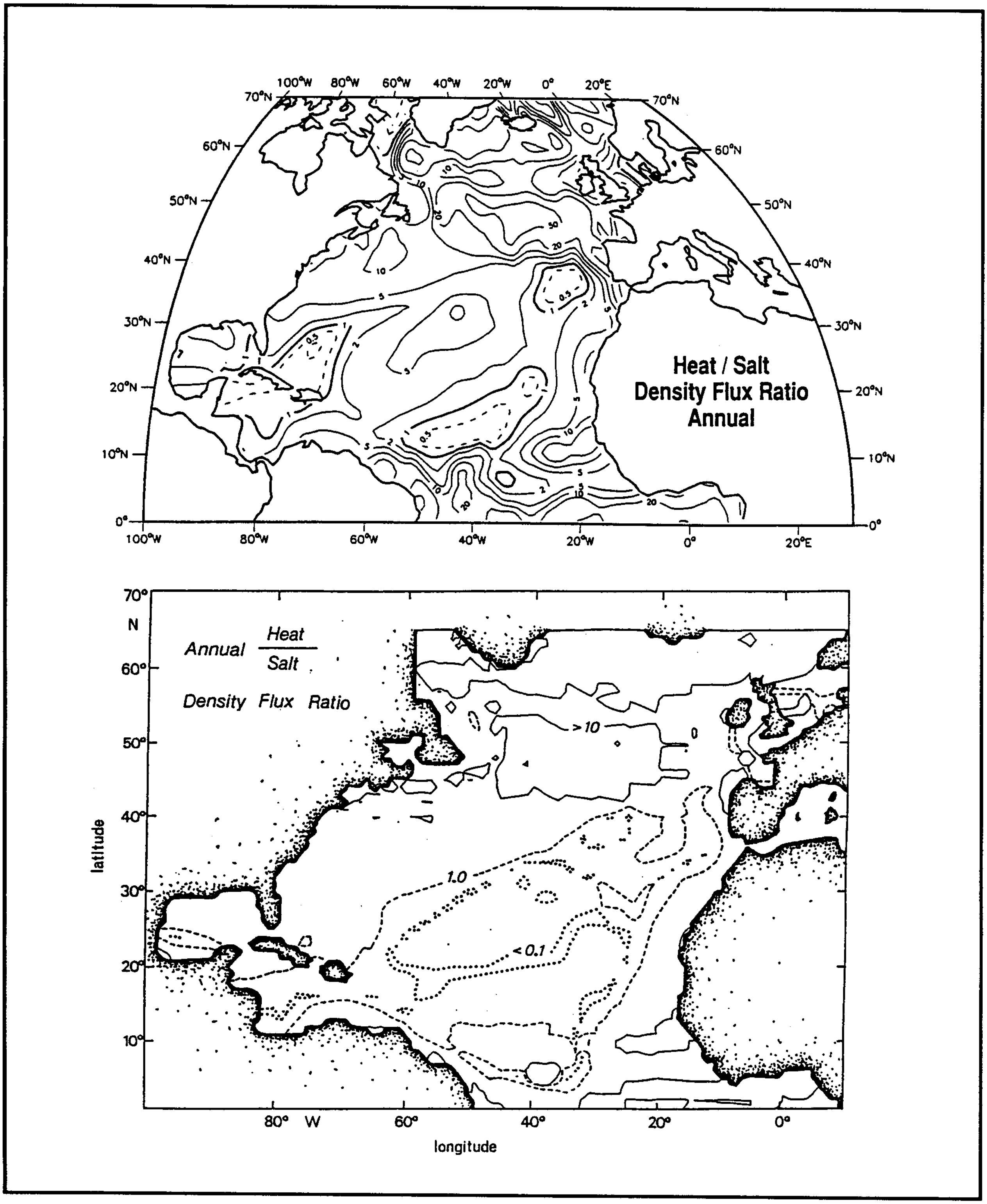



Figure IV.E.2-1. (upper) Absolute value of the ratio of the annual heat and salt density fluxes from Schmitt et al. (1989). (lower) Absolute value of the ratio of the annual heat and salt density fluxes computed by K. Speer, using Isemer and Hasse (1987) evaporations rather than Bunker (1976) (as given in Willebrand, 1992).

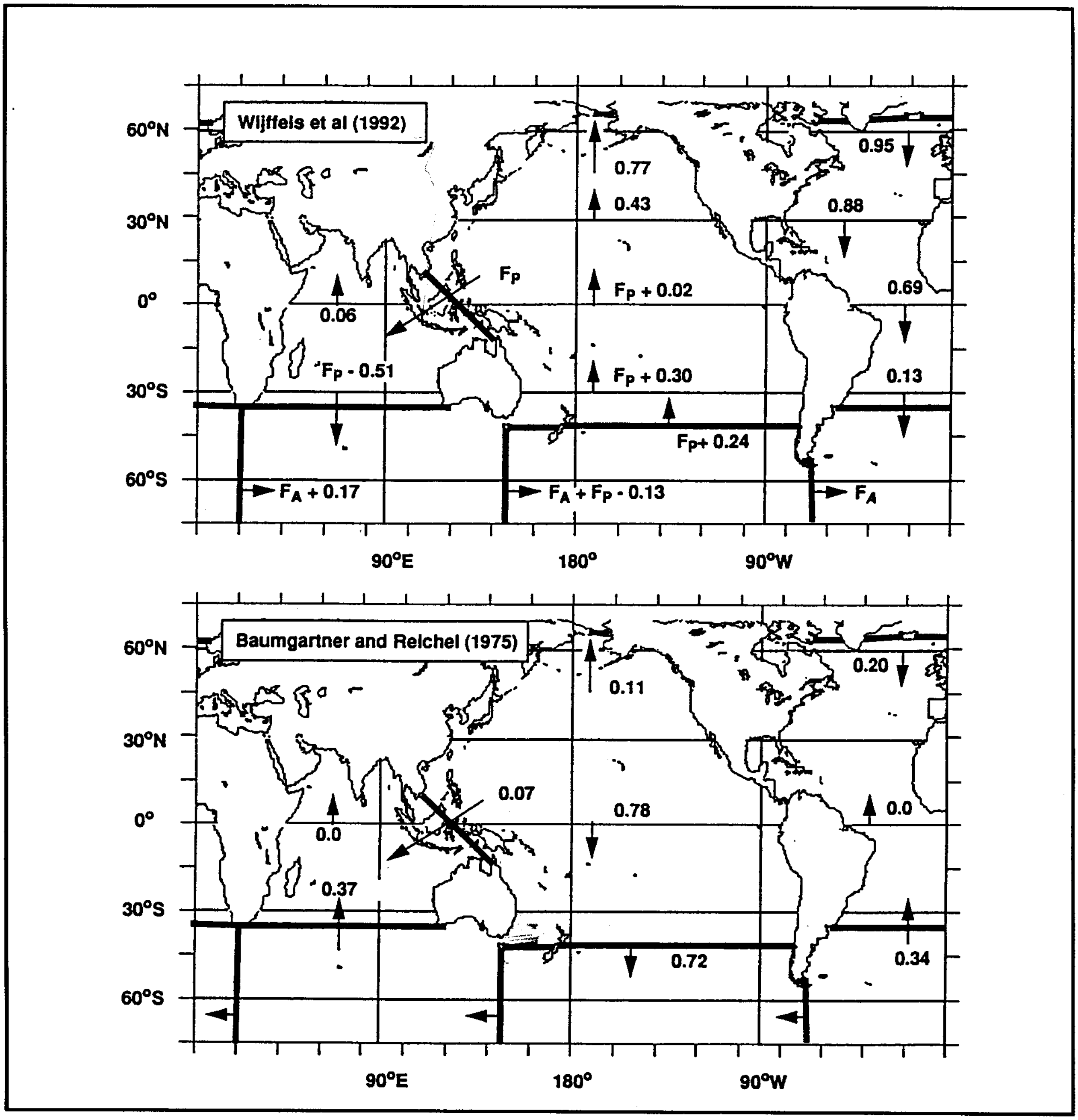



Figure IV.E.2-2. (upper) Net fresh water transports (Sv) in the multiply-connected ocean, according to Wijffels et al. (1992). The fluxes into or out of individual volumes from precipitation, evaporation, and run-off can be summed to give the transport across a trans-oceanic section, but a constant of integration is required to fix the absolute fluxes. The estimated flow through the Bering Strait has been used. Here $F_P$ and $F_A$ refer to the freshwater fluxes of the Pacific-Indian throughflow and the Antarctic Circumpolar Current in Drake Passage, respectively, which are poorly known at present. (lower) Transport of fresh water in the ocean according to Baumgartner and Reichel (1975), assuming zero transport across the equator of the Atlantic and Indian Oceans to develop a global picture. The pattern of fluxes differs considerably between (upper) and (lower).

about 1 m per year! If the salt transport were not also balanced, noticeable differences in the salinity of the whole basin (~0.01) would appear in one year. Since this is not happening, we can safely assume a salt balance, which in turn allows us to calculate the small net velocity of water across a zonal hydrographic section, which is otherwise unobservable. A comparison of one such calculation at 24°N in the Atlantic with the summations of the surface flux estimates is included in Figure IV.E.2-3. The flux estimate suggests that precipitation or run-off at higher latitudes is underestimated (or evaporation overestimated) in the available surface flux fields, though uncertainties are such that the agreement among the data sets north of 24°N is perhaps more remarkable. The recent estimates of flow rate and salinity in the Bering Strait allow us to construct a picture of the global ocean hydrologic cycle from ocean section data alone, thus providing a check on highly uncertain surface flux estimates. Indeed, the differences among the data sets amount to as much as 0.5 x $10^6 m^3/s$ at the equator. This is 2.5 times as large as the flow of the Amazon, by far the largest of all rivers. Our lack of precision in knowledge of the hydrologic cycle over land (Chahine, 1992) pales in comparison with our ignorance of the significantly larger ocean component of the global water cycle.

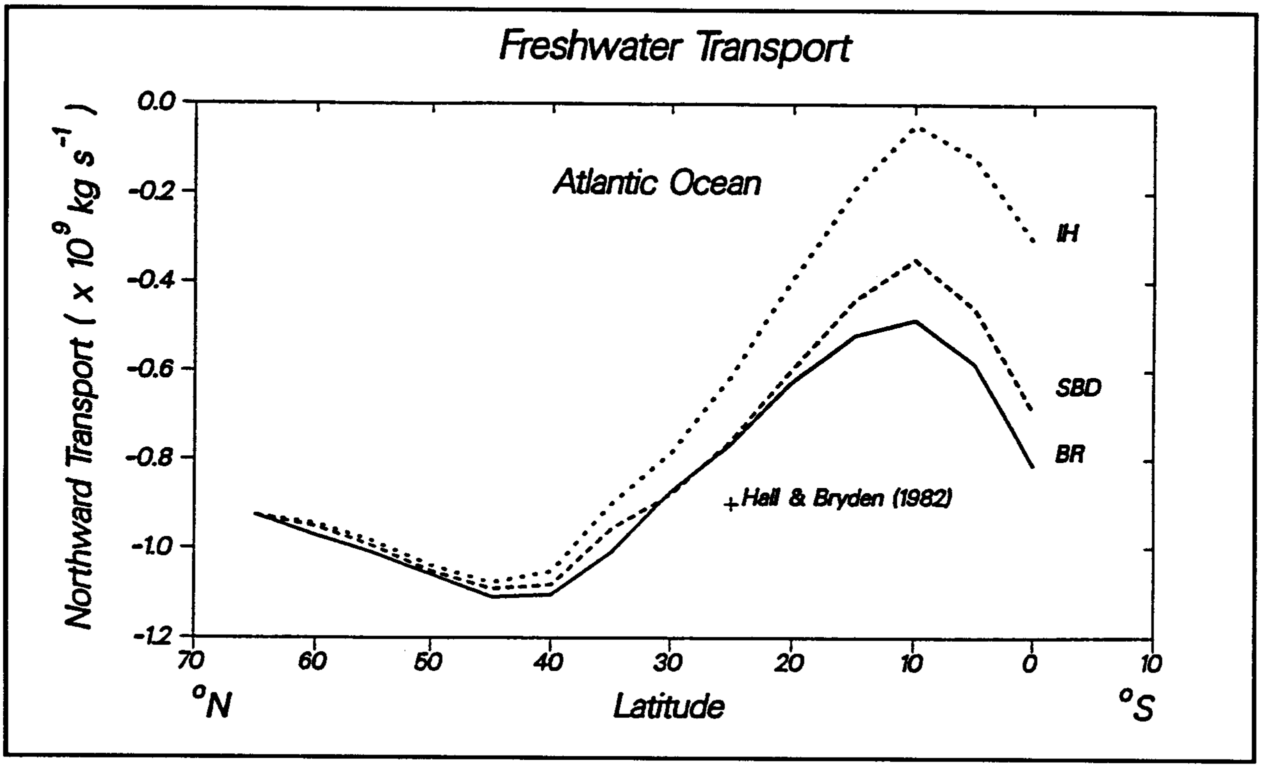



Figure IV.E.2-3. Northward transport (in $10^9$ kg/s) of freshwater as a function of latitude for the North Atlantic Ocean. The estimated flow through the Bering Strait has been used with estimates of surface fluxes from: Baumgartner and Reichel (1975, solid line), Schmitt et al. (1989, dashed line), and the combination of Dorman and Bourke (1981) and Isemer and Hasse (1987, dotted line).

That the transport of water by the ocean is the primary return path for water carried in the atmosphere can be seen by integrating surface water flux estimates as a function of latitude for all the ocean basins (interbasin transports cancel in such integrations). This yields the net meridional flux of water by the oceans (Figure IV.E.2-4). Also shown is the estimate of water flux in the atmosphere by Peixoto and Oort (1983) from rawinsonde climatology. The two fluxes are seen to be largely complementary and are surprisingly consistent given the uncertainties in both estimates. By comparison, river fluxes typically contribute 10% or less to the net meridional water transport.

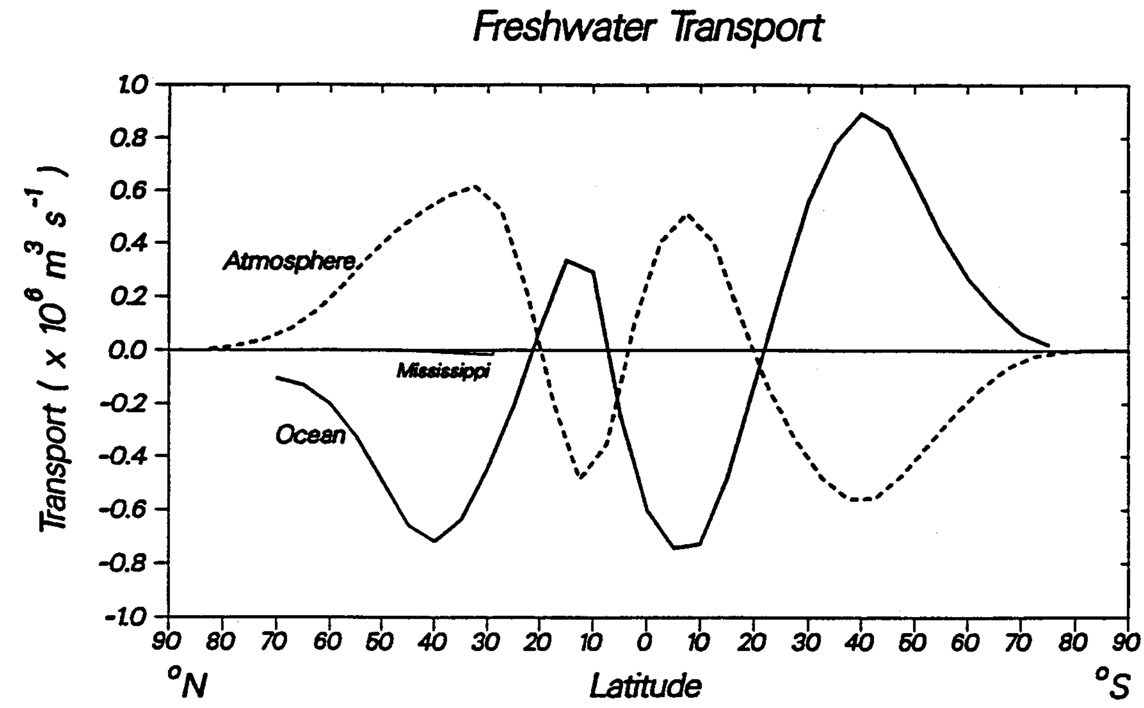



Figure IV.E.2-4. Northward transport of freshwater as a function of latitude in the ocean (solid line) and the atmosphere (dashed line). Ocean transport at each latitude is the sum of the surface water flux estimated for all oceans. Atmospheric transport is derived from Peixoto and Oort's (1983, Table I) water vapor flux divergence values. The transport of the Mississippi River is shown for comparison.

At one latitude, 24°N, recent zonal sections in both the Atlantic and Pacific make possible the calculation of the net water gain between them, since the Bering Strait throughflow requires equal salt fluxes across the two sections. Study of the Atlantic 24°N section, in combination with estimates of the flux through the Bering Strait, requires a southward water transport across 24°N in the Atlantic of 0.9 Sv. Similarly, Schmitt and Wijffels (1992) estimate net water transport across 24°N in the Pacific using the section data of Bryden et al. (1991). They find that the Pacific transports 0.59 Sv of water northward. Thus, the net southward water transport by the ocean across 24°N is 0.31 Sv. This can be combined with river transport at that latitude, which increases southward transport by about 10%. The total southward flux of 0.34 Sv of water agrees well with the estimated northward flux of water vapor in the atmosphere computed by Peixoto and Oort (1983) but is about 0.1 Sv higher than the transport obtained by integration of surface flux estimates.

Since the calculation of water flux is in basic agreement with the Peixoto and Oort (1983) estimate of atmospheric transport, there is no evidence to support the speculation that the "Missing Petawatt", arising from the disagreement between Earth's radiation budget and oceanic and atmospheric heat transport calculations (Bryden, 1993), can be found in unresolved fluxes of latent heat in the atmosphere. While there remains some uncertainty due to unsampled seasonal and interannual variability in the ocean measurements, it seems unlikely that an oceanic flux twice that calculated (required for an additional petawatt) could be obtained, at least at 24°N.

As described previously (Figure IV.E.2-4), the meridional transport of fresh water by the oceans has several extrema. At approximately ±45°, the oceans are required to transport water equatorward, compensating for excesses of high latitude precipitation and low latitude evaporation. At about ±10°, excess water from the net precipitation band of the ITCZ must be transported poleward. These latitudes are thus important sites for monitoring the strength of the oceanic freshwater cycle.

## IV.F. Sea Ice

Sea ice is characterized by area (ice extent and actual ice coverage), thickness, concentration, type (new ice, first-year ice, multi-year ice, etc.), snow depth, surface temperature, surface albedo, and horizontal ice velocity. These properties vary greatly in time and space and are related to atmosphere-ocean interactions. To understand sea ice behavior and its variability, we must measure these characteristics. We can not obtain enough information to quantitatively discuss sea ice variability from in situ observations, because only limited in situ meteorological and oceanographic observations are available from the polar sea ice regions. On the other hand, information on the spatial and temporal variations of some sea ice properties can now be obtained from satellite observations. For example, algorithms exist for the interpretation of data from multi-band passive microwave sensors such as special sensor microwave/imager (SSM/I) and multifrequency imaging microwave radiometer (MIMR), enabling measurement of important sea-ice parameters in the polar regions such as total ice concentration, ice-edge location, multi-year ice concentrations and ice temperature, with an accuracy of six to 10% (Cavalieri et al., 1991; Steffen and Schweiger, 1991). Thus, we are able to monitor temporal and spatial variations of such quantities as "sea ice extent", defined as the boundary between sea ice and ice-free ocean, "actual sea ice area", "open water area", and "multi-year ice extent" using satellites.

The area of ocean actually covered by ice is always smaller than the area determined by passive microwave imaging radiometers because of the existence of open-water leads and polynyas. These features are not resolved by the imagers but are important in determining the heat flux. In terms of estimating the heat flux to the atmosphere, both thermodynamic and dynamic effects are important, though at present very few coupled models incorporate ice dynamics. The dynamics indirectly modify the heat flux through the creation of thin ice, and leads via deformation. In addition, transfers of ice from one location to another, over a seasonal cycle, carry a net heat flux into the atmosphere that can be as large as the average ice growth or decay. For example, in the Arctic Basin over a season there is a net growth of about 0.5 m of ice related to the ice transport out of the area (Moritz, 1992). On a climatic time scale these net fluxes due to ice transport are important. On shorter time scales the deformation-induced leads are also important because moving wind fields can create substantial changes in the lead fraction and modify the surface boundary layer.

An important variable which is critical to sea-ice modeling, but for which data is nearly non-existent, is ice thickness. Accordingly little can be said regarding sea ice thickness variability. This data void is well recognized and possible observational approaches are discussed in Section V.

### IV.F.1. Seasonal variations

The Northern Hemisphere sea ice cover has an average yearly cycle ranging from a minimum sea ice extent of $7.8 \times 10^6$ km$^2$ in September to a maximum of $14.8 \times 10^6$ km$^2$ in March (Parkinson et al., 1987). Because the Arctic is a polar mediterranean sea surrounded by the American and Eurasian continents, it is characterized by thick multi-year ice (2 to 4 m in thickness). About 50% of the Arctic sea ice consists of multi-year ice, and numerous pressure ridges and leads exist within this sea ice cover. Marginal seas (Greenland Sea, Bering Sea, Kara Sea, Sea of Okhotsk, etc.) are not sea ice covered in summer (Tomczak and Godfrey, 1994).

The Southern Hemisphere sea ice cover has an average yearly cycle ranging from a minimum sea ice extent of 4 x $10^6$ $km^2$ in February to a maximum sea ice extent of 20 x $10^6$ $km^2$ in September. The maximum movement of ice edges during the period between summer and winter is more than 1600 km (or 15° in latitude), and the area of sea ice is comparable with the area (14 x $10^6$ $km^2$) of Antarctica. About 80% of Antarctic sea ice is composed of the thinner first-year ice (about 0.5 m in thickness) which disappears in summer. The Weddell and Ross seas are the major sea ice factories. One characteristic feature of Antarctic sea ice covered regions is the existence of numerous polynyas and leads with a variety of scales.

An analysis of sea ice extent in the Arctic and Antarctic and their sum, which is the global sea-ice extent, by Gloerson and Campbell (1988) is shown in Figure IV.F.1-1. The data show very similar seasonal patterns from one year to the next. The global values also reflect a seasonality in total extent akin to the seasonality of the Antarctic sea ice. Interannual variations may be a significant fraction of the regular annual cycle. Although there is little apparent trend in the ice extent of either polar region over the time series, the global maximum extent shows a consistent decrease over the entire period. More recent variability analyses by Parkinson (1991, 1992) indicate no clear systematic trend over the 20 years of data available.

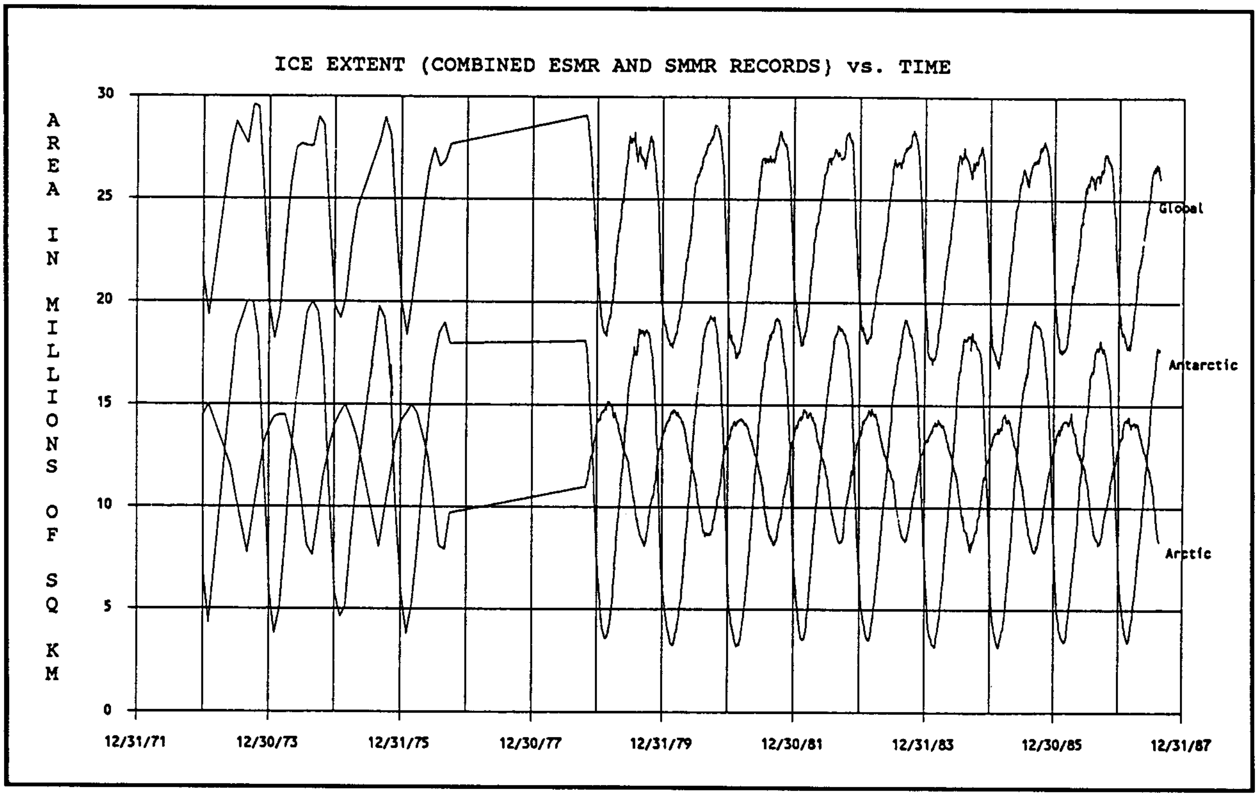



Figure IV.F.1-1. Sea-ice extent in the Arctic, the Antarctic, and their sum (global). The ice extent shown is the area of ocean enclosed by the sea-ice boundaries as derived from ESMR (electronic scanning microwave radiometer) and SMMR (scanning multi-channel microwave radiometer) observations. There was a hiatus in reliable satellite data during the two-year gap 1976-1978. Ice extent is estimated from passive-microwave observations, and errors of these estimates should be small (Gloerson and Campbell, 1988).

It is noted that the polar sea ice extent does not vary seasonally like a sine-curve, and, as shown in Figure IV.F.1-1, that there are differences in the seasonal cycles in the two hemispheres. For the Southern Ocean sea ice extent, a slow expansion (average expansion rate of 2.4 x $10^6$ $km^2$/month) and a rapid retreat (average retreat rate of 3.3 x $10^6$ $km^2$/month) occur. The maximum retreat rate, occurring during the period from November to December, is 6.9 x $10^6$ $km^2$/month. However, for the Northern Hemisphere sea ice extent, there is but a small difference between the average expansion rate (1.8 x $10^6$ $km^2$/month) and the average retreat rate (2.3 x $10^6$ $km^2$/month). The reason for the asymmetric seasonal variation in the Southern sea ice extent is not yet explained fully. Enomoto and Ohmura (1991) showed the area of open waters within the sea ice cover to increase rapidly during the period from September to October although the sea ice extent remained maximum at that time; this causes a rapid retreat of the ice cover during the period from October to December. A similar asymmetric seasonal variation has been pointed out for air temperature around the Antarctica by van Loon (1967). Gordon (1981) suggested that one should consider the effect of oceanic heat flux as well as the atmosphere-ocean heat flux when considering the rapid decrease of sea ice extent from November to December. Other governing factors that influence the asymmetric seasonal variation are the positive feedback effect of sea ice and the effects of sea ice advection due to Ekman transport and water circulation.

IV.F.2. Annual and interannual variations

Sea ice variability is directly affected by the variability of the atmospheric wind field. According to the analysis by Overland and Pease (1982) of the relationship between cyclone paths in the Bering Sea and sea ice distributions, there is a high correlation between large (small) ice extent and southward (northward) shift of the cyclone paths. Niebauer (1980) noted a good correlation between the Bering Sea ice extent and SST for a period of several years studied. The Bering Sea sea ice extent also has a good inverse correlation with the Okhotsk Sea ice extent (Cavalieri and Parkinson, 1987; Parkinson, 1990). Annual variations in both Bering and Okhotsk sea ice extent largely depend upon the relative location of the Aleutian Low (the southward or northward shift) which is connected with ENSO (Niebauer, 1988; Tachibana and Wakahama, 1990).

The Arctic sea ice cover is largely characterized by the existence of multi-year ice. It is considered that variations in total sea ice extent are greatly influenced by variations in multi-year ice extent. Accurate estimation of annual variations in the multi-year ice extent is important for mass balance studies in the Arctic region. According to the recent analysis by Comiso (1990) of passive microwave data during the period from 1979 to 1985, the multi-year ice extent inferred from the winter data is approximately 25 to 40% less than the previous summer ice extent minima, with a difference averaging about 2 x $10^6$ $km^2$. This difference is more than can be explained from present knowledge of the advection and melt characteristics of multi-year ice. Comiso's analysis shows no interannual trend for the multi-year ice area.

Regionally, there are large interannual variations in both sea ice extent and the actual region covered by sea ice for the Antarctic region. This indicates that part of the ice cover is transported to other areas of the Southern Ocean interannually. The Southern Ocean sea ice cover is very sensitive to spatial and temporal variations of global atmospheric pressure, mainly through the Ekman divergence and convergence, because the Southern Ocean is an open sea and the sea ice cover is easily movable. Enomoto and Ohmura (1991) have explained that the seasonal and annual variations in the Southern Ocean sea ice extent are related to the temporal and spatial variations in the circumpolar low pressure trough around Antarctica. Carleton (1981) examined the annual variations in Southern Ocean sea ice cover in relation to the cyclonic disturbances derived from satellite cloud images and found a high correlation between expanding patterns and cyclonic activity, especially in the Weddell and Ross seas.

In summary, the general characteristics of Arctic and Antarctic sea ice are contrasted in Table IV.F-1.

The depth of snow on the sea ice cover also is an important climatological variable. The presence of snow accelerates the positive feedback effect of sea ice. During winter, snow causes increased albedo, providing effective thermal insulation of the underlying ice. Then, in spring and summer, snow melt forms ponds leading to decreased albedo. Another role of snow is supplying fresh water to the upper ocean.

| Attribute | Arctic | Antarctic |
|---|---|---|
| Geography | mediterranean sea (high latitude) | open sea |
| Upper oceanic density stratification | strong | weak |
| Seasonal variation of ice cover | 8 ~ 15 (x $10^6$ $km^2$) | 4 ~ 20 (x $10^6$ $km^2$) (large variation) |
| Characteristics of sea ice | multi-year ice<br>congelation ice *<br>thick (3 ~ 4 m)<br>pressure ridge | first year ice<br>frazil ice **<br>thin (0.5 -1 m)<br>open water area (polynya, lead)<br>iceberg |

* Congelation ice forms slowly beneath first-year, multiyear, or frazil ice.
** Frazil ice is produced rapidly in open water regions.

Table IV.F-1. General comparison of characteristics of Arctic and Antarctic sea ice.

## IV.G. Carbon

The carbon cycle is the subject of OOSDP Background Reports by Merlivat and Vezina (1992) and Wallace (1995) regarding, respectively, monitoring uptake of $CO_2$ by the ocean and monitoring global ocean carbon inventories. The discussion here concentrates on the most important issues.

### IV.G.1. Uses and justification

Current climate models suffer from poorly specified oceanic boundary conditions with respect to heat, freshwater, and carbon fluxes. Regarding carbon fluxes specifically, the distribution of net sources and sinks must be better defined; in other words, the areas and times for which the net air-sea $CO_2$ flux is into the ocean (ingassing) must be clearly separated from the areas and times for which the net flux is out of the ocean (outgassing) (Merlivat and Vézina, 1992). To achieve this, the $CO_2$ fluxes at the air-sea interface and their spatial and temporal variability must be better constrained. Today for instance, models (atmospheric inverse models and ocean models) do not agree on the sign of the annual $CO_2$ air-sea exchange in the Southern Ocean and diverge considerably for other latitudinal bands (Figure IV.G.1-1). It is therefore urgent to obtain, through systematic observation of critical carbon components at the ocean surface, the database required to constrain the atmospheric and oceanic models and improve their predictions.

The main rate-limiting steps for oceanic $CO_2$ uptake are the vertical transport of $CO_2$-laden water (physical pump) and of biological carbon-containing materials (biological pump). Current global estimates of carbon transport to the deep sea are based on models calibrated with $CO_2$ profiles and with the penetration depth of bomb-produced $^{14}C$. These models give estimates ranging between 1.4 and 2.6 Gt C/yr, leaving a global carbon sink in the order of 2 Gt C/yr unaccounted for (Orr, 1993). Systematic observations of circulation, transports and tracers are urgently required to improve the constraints on the models. The biological pump, although considered at steady state at the present time, may well respond to climate change through its intimate links with the thermohaline structure of the upper ocean. Long-term observations are required to detect changes in the rate of the biological pump, at least in some critical regions of the oceans. For example, biological production in the high latitude oceans has been implicated in past glacial-interglacial atmospheric $CO_2$ variations and may well respond to warming.

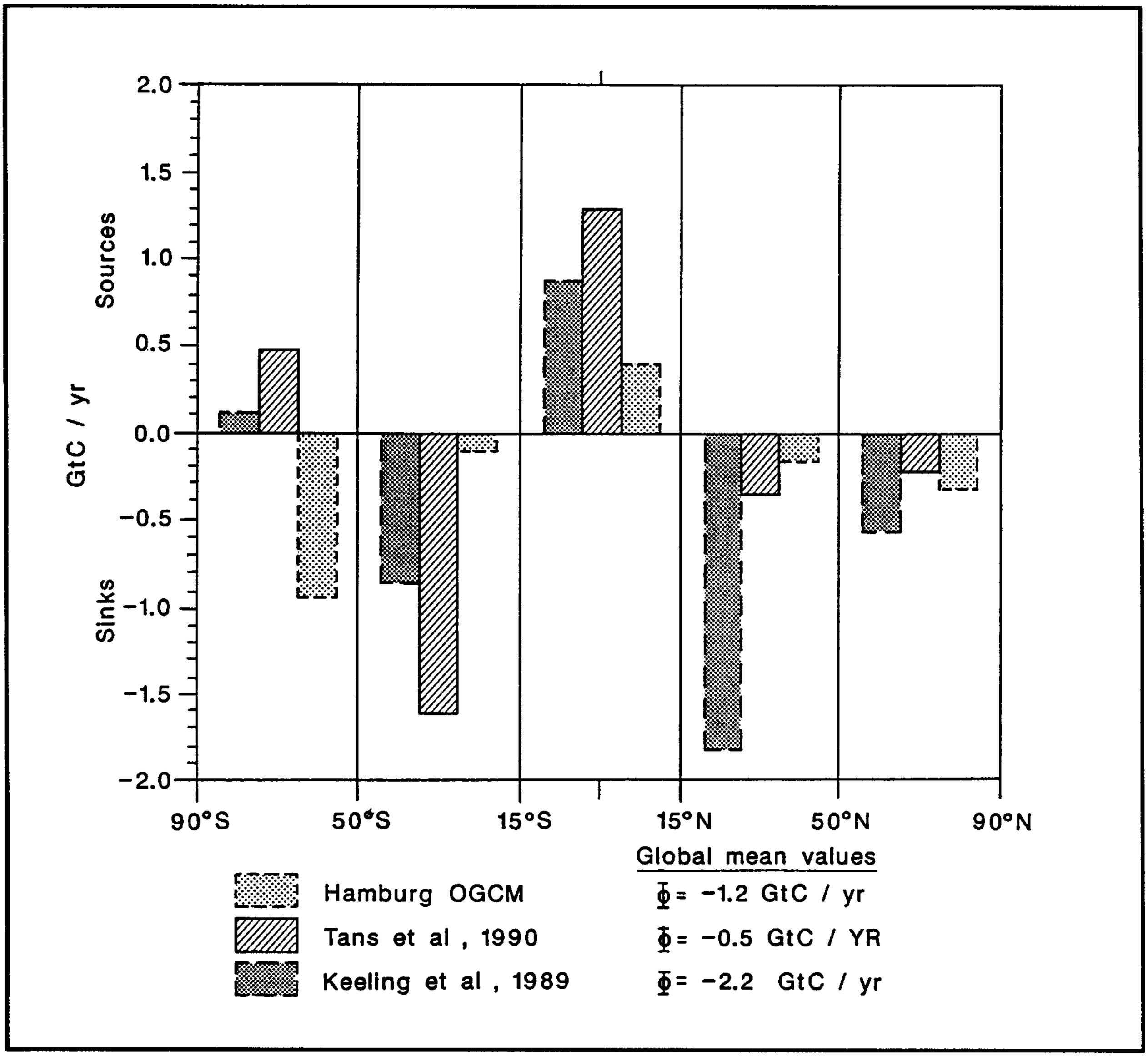



Figure IV.G.1-1. Meridional distribution of carbon dioxide sources and sinks at the surface of the ocean (from Heimann, 1991). Mean annual values in GtC/yr.

Moreover, the absorption of atmospheric $CO_2$ by the ocean should be reflected in changes in the storage of excess carbon in deep waters over decadal time scales. Detection and quantitative assessment of these changes provides a critical test of the predictions of climate models. This represents an integral constraint on the detailed flux estimates. Systematic observations of deep oceanic carbon concentrations are therefore required.

## IV.G.2. Carbon signals, scales of variability, and sampling procedures

To first order, the air-sea fluxes of $CO_2$ can be obtained by bulk parameterization using surface temperature, wind velocity, and the $pCO_2$ difference between atmosphere and ocean. At present, the exchange coefficients used in the bulk formula are uncertain by a factor of two depending on whether they are based on $^{14}C$ inventories or experiments with inert gases (Merlivat et al., 1993). This results in a systematic uncertainty on the flux calculations which may be reduced by work on gas exchange processes. In general, the sampling resolution required for surface measurements will depend on the information required by the inverse atmospheric models (Tans et al., 1990; Keeling et al., 1989) and by the three-dimensional general circulation (physical-biogeochemical) models (Bacastow and Maier-Reimer, 1990; Maier-Reimer, personal communication).

Use of the air-sea disequilibrium of the $^{13}C/^{12}C$ ratio of inorganic carbon with respect to the atmosphere has recently been proposed as an alternative technique to calculate the net air-sea flux of $CO_2$ (Tans et al., 1993). Even though process studies are still required to validate this method, it could represent a cross-check on the direct approach.

Averaged over the globe, the anthropogenic increase in $CO_2$ is 1-2 μatm per year. This is well within reach of present analytical techniques; however, the problem is not with the accuracy but with the variability. Seasonal, zonal and meridional variations in $pCO_2$ far exceed the 10 μatm mean annual signal. The prime requirement for a $CO_2$ observing system is to resolve that variability.

The concentration of dissolved $CO_2$ at the surface of the ocean is determined by physical, thermodynamic, and biological processes. The general circulation pattern of the ocean controls the physical effects which may be best illustrated by the high-latitude low-latitude contrast. For example, deep water formation in the high-latitude areas carries $CO_2$ from the surface waters into the deep ocean, while near the equator upwelling brings $CO_2$ enriched waters to the surface. Thermodynamic effects are closely linked to the circulation pattern of surface waters as they are caused by the change of gas solubility with temperature. These processes have seasonal to annual variability.

The biological effect is caused by the photosynthetic fixation of carbon by primary productivity. Biological drawdown of $CO_2$ in the spring and summer, and regeneration in winter, exert the primary control on the ocean surface $CO_2$ distribution. Availability of nutrients and light control primary productivity and consequently the efficiency of the "biological pump". The time scale associated with biological effects may be very short as shown by recent data from the North Atlantic collected during the 1989 JGOFS bloom experiment. The data indicate that small-scale (10-100 km) variability on the order of 30 μatm, associated with patchiness in biological productivity, was the norm at the time of the cruise (Watson et al., 1991).

How many such observations of $pCO_2$ are needed? We can calculate an order of magnitude for the number of observations needed to define the global air-sea flux to a given accuracy. For example, in the North Atlantic (probably the ocean basin in which $pCO_2$ is most variable and best studied), it has been found that during the spring bloom the 1-$\sigma$ uncertainty at a given point due to natural variations is ~±10 μatm. This suggests that ~100 independent observations would be required to define the mean value at a given point and season to within ±1 μatm. Globally, an error of 1 μatm in the mean would lead to an error in the flux into the ocean of order 0.2 Gt C/yr (Tans et al., 1990). In the ocean, the autocorrelation time and length scales are those appropriate to the passage of eddies (i.e. one month and 100 km). An adequate coverage might therefore require 100 observations for each 100 x 100 km box of ocean for each month of the year.

Such coverage for every part of the global ocean is well beyond our reach. However, the position is not in reality so bleak. Internationally, a considerable effort is now underway to document $pCO_2$

in the surface ocean, and its dependence on season, position, and interannual changes. There are now no major ocean regions in which there are not at least some measurements, and many areas are increasingly well covered. Most of the global oceans appear to be more homogenous in terms of surface $pCO_2$ than the North Atlantic. Furthermore, while such dense coverage cannot be obtained for every part of the ocean, it may be obtained along the routes that merchant ships frequent and in other regions from equipped drifters.

It is apparent that the $pCO_2$ in oceanic surface waters varies dramatically in parts of the world away from the tropics, due both to biological and temperature effects. Heating of the surface results in an increase in $pCO_2$ such that, other things being equal, summertime values would be high. However, in most cases, biological productivity fixes carbon from the water and has the opposite effect. The effect that dominates depends on the location. The gas transfer coefficient also varies seasonally, because in winter at temperate latitudes winds are higher. The seasonality of the transfer coefficient is out of phase with the dominant biological effect on $pCO_2$ at higher latitudes, so that the annual flux through the sea surface tends to be evened out.

Satellite-based measurements of ocean color offer the only means to map variations in biological activity quasi-synoptically at the global scale. Regional parameterizations of photosynthesis as a function of ocean color are being developed within JGOFS. Research has shown that these parameterizations must include the seasonal cycles within each region. Global and systematic validation of the ocean color algorithms will require time series of surface observations in different water masses. The global wind field as measured by satellite or from the output of NWP models is needed for the exchange coefficients.

The $^{13}C/^{12}C$ ratio of $CO_2$ dissolved in ocean waters is potentially a powerful tracer of carbon cycling. There is little data available on the $^{13}C/^{12}C$ ratio at the ocean surface and the analyses of $^{13}C/^{12}C$ collected on cruises used for $pCO_2$ observations could greatly reduce the uncertainty in estimates of ocean carbon uptake that are now based on $pCO_2$ data and models of the carbon cycle. The sampling strategy will need to resolve seasonal and spatial changes in $^{13}C/^{12}C$ for surface waters. Provided adequate standards are available for the measurement of $^{13}C/^{12}C$, an accuracy of $\pm 0.04$ per mil should be achievable, which will provide an accuracy comparable to that obtained from $pCO_2$ measurements.

Present biological and geochemical evidence indicates that the downward transport of organic carbon on time scales of days to weeks is tightly coupled to the photosynthetic processes that draw down the surface $CO_2$. Therefore, the scales of variability of vertical organic carbon flux are similar to the scales just described for biologically-driven surface $pCO_2$ anomalies. Direct observations of these fluxes (by sediment traps or biogeochemical proxies) at the space and time scales required to resolve annual to interannual variability cannot be envisaged at this time. Quantitative knowledge of these fluxes will depend on linking surface observations, such as those used to map $pCO_2$ anomalies, with physical-biogeochemical process models. Adequate process models will result from studies aimed at understanding the dynamics of biogeochemical cycling undertaken by JGOFS.

Although the biology and chemistry of the open ocean have been studied extensively for over a century, there have been relatively few attempts to describe the large-scale distribution of biogeochemical properties or the pattern of natural boundaries where state changes occur. There are several long time series where spatial averaging has been done (in the Atlantic, the Continuous Plankton Recorder survey and, in the Pacific, the California Cooperative Fisheries Investigation (CalCOFI)). These have shown that biological variations at mid- and low-latitudes have a "red" spectrum. There also is strong evidence of important interannual variability, especially in the carbon cycle (McGowen and Wiebe, 1991).

In terms of sampling requirements, it is important to realize that the ocean comprises distinct marine ecosystems with distinct biological dynamics. Although these ecosystems have been identified, their internal dynamics and patterns of spatial and temporal variability remain poorly known and are the subject of intensive studies by the JGOFS program. For example, the N. Atlantic and N. Pacific ecosystems have completely different dynamics and patterns of spatial and temporal variability. To interpolate global surface $pCO_2$ measurements, regional parameterizations of the relationships between $pCO_2$, chlorophyll, and temperature will have to be developed. Ecosystem-specific biogeochemical algorithms will be later incorporated into the three-dimensional models for validation and ultimately for global data assimilation.

Variability on the vertical scale imposes further constraints on observations of biogeochemical processes. Vertical length scales for photosynthesis in the open ocean are on the order of 10-30 m. Critical photosynthetic processes occur at depths that cannot be monitored by satellites, VOS or drifters. Vertical length scales for the remineralization of carbon to $CO_2$ are longer, on the order of 100-200 m for the top kilometer of the ocean. All indications to date point to large horizontal length scales (1000s of kms), although mesoscale eddies and rings introduce additional variability in vertical structure. At the very least, monitoring at time-series stations requires measurements at the appropriate vertical scales for different representative ocean regimes.

In terms of detecting the long-term change in $CO_2$ storage in the deep ocean arising from increasing anthropogenic levels of atmospheric $CO_2$, accuracy becomes a prime concern, because variability in deep oceanic waters is not nearly as strong as in the upper ocean. To be able to detect the signal after 10 years, the required accuracies are at minimum $\pm 1$ µmol/Kg for total $CO_2$ and $\pm 1$ µmol/Kg for total alkalinity. To be applied on a global scale, the calculation of storage from the measurements must resolve the effect of the mixing of different water masses. There is hope that this difficulty can be circumvented by the use of transient tracers such as $^3$H-He, $^{14}$C, and CFCs. There is little doubt that transient tracer data and models have provided the most robust estimates of excess $CO_2$ to date.

Given knowledge of the vertically and horizontally resolved water transport across a zonal oceanographic transect, together with measured concentrations of total $CO_2$ along the same transect, the net flux of $CO_2$ across the transect can in principle be calculated using techniques described in V.F for heat and fresh water. This offers the possibility of inferring the distribution of global sources and sinks of $CO_2$ at the surface of the ocean. Substantial uncertainty may arise because of temporal variability, especially in the Ekman transport.

## IV.H. Water Mass Renewal, Circulation, and Inventories

As consequences of surface wind stress and the air-sea exchanges of water and heat, surface waters in selected regions of the ocean are made denser than adjacent or subjacent ocean waters. Subsequently, these waters enter the ocean's interior and waters with different properties rise at other locations. This procedure, referred to as water mass renewal, is critical to global climate because constituents in the atmosphere are absorbed into surface waters and subsequently are transported into the interior. There they are stored, and perhaps modified, until brought again to the surface by the large-scale circulation of the ocean, including upwelling within the ocean's interior. This complex system of water mass renewal plays a major role in controlling climate change, because the processes and rates of these phenomena determine the storage and transports of chemicals (including gases of import) and heat by the ocean. In fact, for climate change on time scales of years to centuries, these phenomena may play a controlling role.

The rates of exchanges between ocean and atmosphere and the ocean circulation could be used to determine the changing ocean inventories of heat and chemical species. Thus, measurements either of the inventories or of the air-sea exchanges and ocean circulation are crucial to an ocean observing system for climate. The net transport of heat and fresh water meridionally and between ocean basins has been discussed in Section IV.E.

Moreover, measures of the ocean circulation are also needed for the development and validation of models of the ocean circulation. These measures include: the transports of mass, heat, and selected chemical species between the major ocean basins; transports of the major boundary currents; information on the interior velocity fields (e.g., mid depth flow or modal structure of velocity); and estimates of eddy activity. Most of the mechanical energy of the ocean is in the form of potential energy, which can be estimated by measuring the density field. Long-term changes in the wind forcing will change the strength and/or location of the major ocean gyres and be reflected in the density field. For validation of ocean models, the strengths and locations of major ocean gyres, as well as the conversion rates of intermediate and bottom water masses, are key measures.

We briefly describe here two modes of water mass renewal and associated circulation: 1) deep convection, associated circulation, and mid-depth upwelling; and 2) surface water modification by air-sea exchanges, subduction under adjacent water masses as under the action of surface wind stress, and subsequent circulation as intermediate waters. Obviously, the two modes are coupled. Then, we discuss briefly inter-basin transports and mention the need for other circulation measures in the interior ocean.

Formation and circulation of deep and bottom water in the world ocean. These phenomena are critical to climate variations on time scales of decades to hundreds of years. Time scales of water mass renewal on basin-wide averages are reasonably well estimated; regional time scales of renewal generally are not known and may vary greatly. Improved knowledge of the rates of large-scale ocean circulation is required. Such knowledge can come from monitoring the global inventories of properties, the transports and properties of deep boundary currents, and the conditions in regions of surface or near-surface formation of dense water. Simulations of circulation for ranges of possible high-latitude surface conditions are just beginning but are essential in planning meaningful observations and for extending the necessarily limited observational network.

The deep and bottom waters of the ocean are replaced through a series of processes over relatively long time scales. We may begin with the formation, at or near the sea surface, of waters dense enough to reach the deep ocean by sinking. Although agreement is not universal on operative mechanisms for deep convection, potential candidates have been identified and are under study; different processes are active in different areas (Killworth, 1983). This deep water mass formation is thought to occur in only a handful of locations (Warren, 1981): around Antarctica, in the Arctic basins, and in the Labrador and (European) Mediterranean seas.

Relatively warm and salty waters from the Atlantic are carried under the action of the wind-driven circulation into the basins of the Arctic Ocean. Entering the high-latitude Arctic they sink and spread filling both Canadian and Eurasian Basins at intermediate depths. For a recent review of the thermohaline circulation of the Arctic basins, see Aagaard et al. (1985).

Open-ocean deep convection is the candidate formation mechanism for the extreme deep water properties formed in the Greenland Sea. This Greenland Sea Deep Water is one of the parent waters for the other deep water types of the region: Norwegian Sea Deep Waters and Eurasian Basin Deep Water. In the high latitude basins of the Arctic, convective processes occur at the shelf edges resulting in the formation of very dense waters. Canadian Basin Deep Water, formed near the wide shelves of that basin, fills the deep basin and is another parent water type for the major deep waters of the Arctic Ocean. Deep Waters of the high latitude Canadian and Eurasian Basins exchange with those of the Greenland Sea via Fram Strait.

The formation of Greenland Sea and Canadian Basin Deep Water, or other high latitude parent waters, is dependent upon the salt content of the Atlantic Water and Arctic surface water; e.g., Clarke et al. (1990) conclude that multi-year variability in salt content of these waters probably can control Greenland Sea Deep Water formation. In this regard, remarks are in order regarding the influence of the (European) Mediterranean Sea on the salinity of the ocean.

Bottom waters (Mediterranean Deep Waters) are formed by deep-reaching, wintertime convection in the northwestern Mediterranean—in the Gulf of Lyons over the fan of the Rhone River. This deep convection was observed in 1969, 1970, and 1975, but not in 1972 (see e.g., Stommel, 1972; Gascard, 1973; Gascard, 1978). The formation process is similar in many ways to that of Labrador Sea Deep Water (Killworth, 1983). Observations made in the winter of 1987 describe in some detail the surface exchanges and the hydrographic and current variations associated with a sequence of convective events resulting in Mediterranean Deep Water formation (Leaman and Schott, 1991; Schott and Leaman, 1991). Intermediate water is contributed to the Mediterranean from the eastern Levant and Ionian Basins of the Mediterranean. The Levantine Intermediate Water is the principal source of the high salinity necessary for the formation, under cooling conditions, of the Mediterranean Deep Water. Inflow of North Atlantic water to the Mediterranean through the Straits of Gibraltar is balanced by an underlying outflow of very high salinity (36.5-38.4) water and by evaporation over the Sea. The exchange was monitored in 1985-1986 using moored bottom pressure recorders and current meters, CTD (conductivity-temperature-depth probe) and micro-structure measurements, and sea level gauges (Bryden et al., 1988). The outflow was estimated to be 0.76 Sv with an effective salinity of over 38, yielding a net evaporation over the Mediterranean basin of 55 cm/yr. Clearly climatic variation in evaporation over this basin could affect both the rate of outflow and its salinity. Moreover, because of the far reaching effects of this salt input to the global ocean, this exchange is important to climate studies. Based on observations from 1910 to 1987 (Lacombe et al., 1985; Leaman and Schott, 1991), there is evidence that since the 1960s both salinity and potential temperature of the deep water in the northwestern Mediterranean have been increasing at rates larger than can be explained by observations errors or differences in techniques (~0.03 per decade for salinity and ~0.03°C per decade for temperature). Density of these waters has not changed significantly. Leaman and Schott (1991) point out that it is unknown whether this change is due to an increase in salinity of the Levantine Intermediate Water or to long-term climate variations.

At depths near 1000 m the influence of the Mediterranean is seen throughout most of the North Atlantic Ocean at mid latitudes as a major source of salt (Reid, 1978). Moreover, Reid (1979) inferred that the distribution of the core of high salinity water from the Mediterranean Sea flows northward offshore of Europe, and that it outcrops in the Labrador Sea and near 60°N is shallow enough to extend through the Faeroe-Shetland Channel into the Norwegian and Greenland Sea area. This implies that the European Mediterranean may have an influence on the production of North Atlantic Deep Water components. Thus, monitoring of its outflow and salinity should be considered as part of the observing system. The circulation to high latitudes of relatively salty water and its exposure to conditioning at the surface by air-sea exchanges or at Arctic shelf edges is critical to the deep water formation process and thus to thermohaline circulation.

Arctic Intermediate Water (AIW), slightly less dense than Norwegian Sea Deep Water, is formed in winter at the sea surface north of Iceland and in the Greenland Sea, north of Jan Mayen Island. Winter cooling and vertical mixing produces fresh, well-oxygenated water called upper AIW by Swift and Aagaard (1981). This water spreads laterally along isopycnals into the Norwegian Sea. In winter the isopycnals corresponding to this water outcrop at the sea surface in the central Greenland and Iceland cyclonic gyres. Thus, upper AIW may be ventilated and replenished each winter. Swift and Aagaard conclude that the minimum annual production rate of upper AIW is 0.84 Sv. The AIW formed in the Greenland Sea is relatively warmer and saltier than that produced in the Iceland Sea due to more prolonged mixing with inflowing Atlantic Water above it, though both have nearly the same densities. AIW spreads southward to the Denmark Strait and eastward into the Norwegian Sea.

Swift et al. (1980) report that this AIW is the principal dense component of the Denmark Strait overflow—Norwegian Sea Deep Water contributing less than 10%. The resulting outflow forms the densest (lower) component of "new" North Atlantic Deep Water (NADW). The volume outflow at Denmark Strait is estimated to be 2.9 Sv (see e.g., Dickson et al., 1990). The major participation of AIW in this lower NADW production and the fact that this water is formed annually at the sea surface, may imply that dense NADW is significantly more sensitive to climate perturbations affecting the sea surface than previously thought.

The outflows over the Faeroe Islands–Iceland Ridge and through the Faeroe Bank Channel (between the Faeroe Islands and Scotland) are comprised of a mixture of AIW with underlying Norwegian Sea Deep Water. This outflow with local entrainment is estimated at 2.7 Sv (see e.g., Dickson et al., 1990). This outflow may be less sensitive to interannual changes at the sea surface due to longer residence times of the outflowing waters. The outflow between Iceland and Scotland continues southwestward along the eastern flank of the Reykjanes Ridge and then westward through the Gibbs Fracture Zone to form middle NADW.

The combined flow of these traditional lower and middle components of NADW denser than $\sigma_0$=27.8 kg/m$^3$ flowing southward as a bottom western boundary current at 63°N off east Greenland has been estimated by a two-year long array of direct current measurements to be 10.7 Sv (Dickson et al., 1990). This would imply entrainment of 5.1 Sv after outflow over the Greenland-Iceland-Shetland ridge system. Clarke and Rapp (1984), using short-term current measurements obtained in 1978, estimated the westward transport of waters denser than $\sigma_0$=27.8 kg/m$^3$ south of the tip of Greenland to be 13.5 Sv.

The traditional upper component of NADW is formed by wintertime, open-ocean deep convection in the Labrador Sea. In 1976, this was observed directly by Clarke and Gascard (1983) who estimated that 3.9 Sv of new Labrador Sea Deep Water (LSDW) was formed, as inferred from property distributions before and after convection. It is not known if that was typical for a year in which LSDW is formed. As discussed in Sections I.B.2 and IV.A, the formation of Labrador Sea Deep Water is quite dependent on surface layer salinities, extent of ice cover, and winter time atmospheric conditions. There are years (e.g., 1967-1970) in which little or no new LSDW is formed.

Recently, Pickart (1992) described a fourth component of NADW as part of the deep western boundary current flowing southward in the North Atlantic. He showed this component to be less dense than LSDW formed in the central Labrador Sea and so not a modification of that water. Rather, Pickart identified the source of this shallowest component (with temperatures of 4-5°C) to be in the southern Labrador Sea inshore of the North Atlantic Current (west of 40°W), where he believes it is formed by convection. The rate and frequency of formation of this water mass are not yet clear. However, as Pickart notes, the continuity of CFC-tritium signal in this water in the North Atlantic indicated it is formed regularly. Whether the relative uniformity of its characteristics, as observed at different times and locations in mid-latitudes, is indicative of no interannual cessation in production or of mixing and entrainment in the deep western boundary current remains to be determined.

The circulation of Denmark Strait and Iceland-Scotland overflow waters in the North Atlantic has been discussed by Swift (1984). The components of NADW proceed as deep western boundary currents and recirculations southward through the North and South Atlantic. It now seems likely that the properties in this southward flow are much modified by the recirculations and interruptions (path changes) associated with major bathymetric features.

Nevertheless, within the Argentine Basin of the South Atlantic the NADW is still prominent as a southward boundary current above the northward flow of the Antarctic bottom waters. South of 40°S it begins to turn eastward, part returning around the anticyclonic subtropical gyre and part joining the Antarctic Circumpolar Current (ACC) (Reid et al., 1977). Its waters penetrate the ACC to 50°S in this region reflected by high salinity, high temperatures and low nutrient concentrations. These influences are seen in the Circumpolar Deep Water (CDW) of the ACC around the entire Southern Ocean.

In a zonal band near 50°-60°S, large volumes of deep and bottom waters are transported eastward from ocean to ocean by the Antarctic Circumpolar Current. Isopycnals tilt upward toward the south in response to the eastward flow. Thus deep waters, including influences of the NADW which are stronger in the Atlantic, cross the ACC and are found in the near-surface regime south of that current.

Interaction of this relatively salty and warm Circumpolar Deep Water with cold shelf waters, sometimes influenced by contact with the undersides of ice sheets, over the shelves and shelf edges of Antarctica results in waters dense enough to sink to the bottom or at least to great depth. The details of the process by which this occurs are still in question and may differ somewhat depending on location. For the present climate state, this deep/bottom water formation occurs at significant rates principally in the Weddell and Ross seas, but to lesser extents in other selected regions (Warren, 1981).

Estimates of the total volume formation rate of dense water at the shelf edge by mixing of shelf waters with CDW varies from 6-10 Sv. Based on examination of hydrographic variables and tracers, this water entrains additional deep waters during the sinking process so that the total production of "new" Antarctic bottom water may be nearer 10-15 Sv. This has proved to be a difficult quantity to estimate well for several reasons, including the facts that formation regions are distributed around Antarctica and not all potential formation regions have been well surveyed, not all new water is dense enough to sink to the bottom, and it is expensive and difficult to make observations of either the rates at the formation sites or the outflows from the continental slopes.

It is possible that deep-reaching, open-ocean convective chimneys also help to ventilate the subpolar, cyclonic gyres of the Southern Ocean. However, the only potential observation of this phenomenon indicates a very small spatial extent (10s of km), and detection would be fortuitous.

These newly conditioned deep/bottom waters are entrained into the circulation systems south of the ACC, and then largely are entrained into that current. Thus, they modify the eastward flowing CDW adding constituents picked up during their conditioning at the sea surface.

In the South Atlantic, newly formed bottom waters from the Weddell Sea pass beneath the ACC as a bottom boundary current aided by the bathymetry in this area. Thus, the supply of bottom waters to the Atlantic consists both of this "new" bottom water and of CDW from the ACC. Except for the extreme North Atlantic where NADW of local origins occupy the densest layers, the bottom waters of the Atlantic are renewed by this flow. Using a 14-month array of current meters Whitworth et al. (1991) estimated the transport of the deep western boundary current into the Argentine Basin north of the Falkland Plateau. They found the transport of new Antarctic bottom water ($\theta < -0.2°C$) to be 2.5 Sv. The total transport into the Atlantic of new bottom water plus CDW colder than 0.2°C (the minimum deep temperature passing through Drake Passage, and thus possibly entering from the Pacific) was 8.2 Sv (a bottom water input to the Atlantic comparable to that of NADW from the north). All bottom waters of the Indian and Pacific oceans are supplied by CDW from the Circumpolar Current alone (Mantyla and Reid, 1983).

Distribution of these dense waters from their convection sites to all the ocean basins is by a global circulation system (the "thermohaline circulation") consisting of abyssal boundary currents and recirculations, lateral spreading from these currents into the basins, and slow upward movement and modification (Warren, 1981). A simple physical framework for this circulation system exists (Stommel, 1957; Stommel and Arons, 1960a, b) and much descriptive information on the boundary currents corroborating that framework has been gathered (Warren, 1981). On the other hand, some of the limited available interior ocean observations seem at odds with this framework. A rigorous theoretical treatment including time dependence and realistic bathymetry is emerging (e.g., Pedlosky, 1992; Pedlosky and Chapman, 1993; Kawase, 1993) but measurements adequate to confirm or deny the framework are largely lacking.

Nevertheless, we know enough to be able to state with reasonable certainty where the principal source regions are, the paths of (most) major deep boundary currents, and the order of magnitude of many of their transports (in some cases we have better estimates). This information on the thermohaline circulation is derived largely from observations made within the past 20-25 years—most within the past decade—and the present situation should not be considered as representative of either the past or the future. With this information we can estimate the residence times of waters in the major ocean basins. To be more precise, we can estimate only the time it would take to supply each major basin (say the North Pacific) with enough relatively new water to replace all the deep waters of that basin assuming the present boundary current transports do not change. These residence times vary from the order of 10 years for the Scotia Sea (Locarnini, 1991) to 1000 years for the North Pacific (Broecker and Peng, 1982; Nowlin et al., 1991).

Moreover, the rates of renewal, or thermohaline overturning, vary greatly from ocean to ocean—and perhaps from individual basin to basin. The inflow of Antarctic bottom water to the Pacific along the western boundary of the South Pacific is estimated as 15-20 Sv (Warren, 1973; Nowlin et al., 1991) while that into the Indian Ocean at 32°S is estimated to be 27 Sv (Toole and Warren, 1993). The volume of water to be renewed in the former is many times that in the latter leading to a much smaller mean residence time for the Indian Ocean. The mechanisms responsible for this difference are unknown, but are one objective of a study of the Indian Ocean being undertaken as part of WOCE (U.S. WOCE, 1993).

These estimated residence times are basin-wide averages. But, the renewal rates are not likely to be uniform within ocean basins. The average values of vertical diffusion needed to balance the upward motion at mid depths within the interior ocean while maintaining observed distributions of temperature and density are considerably larger than direct measurements (e.g., Ledwell et al., 1993) from intermediate levels in the open ocean. It seems likely that vertical diffusion may be selectively large in major currents or near steep bathymetry. Thus, much of the upward return of deep/bottom waters may take place in selected areas. If most of the deep water entering a basin is being returned to the surface layers relatively rapidly, that basin of the ocean may not be an effective storehouse for components taken from the atmosphere. Thus, such a basin would be less effective as a buffer against increases in the atmosphere of undesirable chemical species.

Because ocean waters contain gases exchanged with the atmosphere while at the surface, the deep convection and subsequent transport into the world ocean represents a (temporary) removal from the atmosphere of gases such as carbon dioxide and chlorofluorocarbons. This system of circulation also causes heat transfers (e.g., increasing the transport of a cold equatorward deep boundary current is equivalent to increasing the poleward heat transport by the ocean). Therefore, measures of the transports of the abyssal boundary currents are important to estimate rates of renewal from the atmosphere of a variety of potentially hazardous or climate changing substances and to oceanic heat and freshwater transports and balance.

If surface conditions change, the transports of the thermohaline circulation may be changed in either of two ways: the rates or locations of deep convection may be altered, or the upward motion of waters within the basins may be altered. (There is some speculation that changes in the deep convection within the Weddell Sea have occurred over the past two decades.) Such changes could be quite difficult to observe directly. However, in regions where surface conditions are known to vary such that major deep water formation rates change dramatically, time series of stations or sections could be instituted (or continued) with good effect. One such location is the Labrador Sea, source region for the upper NADW, where, as first observed by Lazier (1980) and studied further by others mentioned elsewhere in this document, the formation rate may vary greatly or be halted temporarily over decadal time scales.

The consequences of these changes could be observed through measuring the transports of the boundary currents or observing the distribution of water mass characteristics within the basins. Based on present knowledge, it would be difficult to approach the problem through boundary current measurements alone. However, repeated transocean sections may be used to estimate the changes in hydrographic properties. These indicate changes in the volumes and characteristics of water masses from various distinct sources. The deep, transatlantic hydrographic section at 24° has been occupied three times over the past 35 years: 1957, 1981, and 1992. Parrilla et al. (1994) showed that the waters between 800 and 2500 m have warmed and that the 35-year difference is quite uniform across the east-west extent of the Atlantic. The maximum warming found at 1100 m seems to be occurring at the rate of 1°C/century. This is consonant with trends in model results for increased atmospheric $CO_2$ but occurs in the interior rather than at the surface.

In addition to estimating changes in thermohaline circulation, regular observations of selected water characteristics, including density, in the major ocean basins would yield information needed to monitor changes in the large-scale, wind-driven circulation gyres. At relatively long repeated intervals (say decades) such measurements would yield valuable information on the changing global inventories of carbon and other chemical species, including trace gases.

<u>Ventilation of the ocean thermocline.</u> The interaction of the ocean with the atmosphere in mid and high latitudes may be critical in controlling the variability of climate on time scales from several years to decades. This occurs in two ways: directly, via heat and moisture exchange between ocean and atmosphere; and indirectly by the renewal of the upper to intermediate waters of the ocean (called ventilation of the ocean thermocline). Key problems are related to the frequency, intensity and mechanisms of ventilation.

The subduction process, by which surface waters are modified by ocean-atmosphere exchanges and then carried into remote interior regions of the ocean circulation gyres, leads to the formation of near surface and intermediate waters. Although new waters are formed and subduct each year, the formation rates may differ considerably. The cumulative effect can be seen in the distributions of the various mode waters across the major gyres.

The formation and subsequent distribution of mode waters/intermediate waters within the wind-driven ocean circulation has been studied and reported for many decades. (For examples, see: Sverdrup et al., 1942; Worthington (1959) regarding the 18° water in the North Atlantic; Masuzawa (1969) regarding the subtropical mode water of the North Pacific; McCartney and Talley (1982) regarding the subpolar mode water of the North Atlantic; and McCartney (1977 and 1982) for Subantarctic Mode Water and subtropical mode water recirculation. There are in addition many intermediate, thermocline waters formed elsewhere, e.g., in the gulfs leading into the Indian Ocean.)

These thermocline waters can have significant effects on climate-related exchanges. As an example, the cool, low salinity Antarctic Intermediate Water and the Subantarctic Mode Water formed within the northern boundaries of the Southern Ocean inject cool water into a low density stratum controlling the depth of the Southern Hemisphere's thermocline, by limiting downward migration of tropical heating. Antarctic Intermediate Water helps balance the global water budget by transferring polar excess precipitation into the evaporative subtropics. It also injects high oxygen water into the lower thermocline, confining the subtropical oxygen minimum layers to mid-thermocline.

Luyten et al. (1982) proposed a simple, elegant model for this process of "thermocline ventilation". The concept has subsequently been elaborated both numerically and analytically; for references, refer to the recent papers by Liu (1994) or Liu et al. (1993).

Inter-basin transports. The transports of mass, and of heat and fresh water, between major ocean basins are required for model formulation and validation. Changes in these transports may also signal important shifts in global ocean circulation, and so global heat and freshwater balances.

The principal inter-ocean exchanges are transports: of the Antarctic Circumpolar Current; from the Pacific to the Indian Ocean through the Indonesian Archipelago; and through the Strait of Gibraltar. A small but important (to the global water cycle and to ocean ventilation in the Arctic basins) volume transport of approximately 0.8 Sv has been observed through the Bering Strait from the Pacific Ocean to the Arctic Basin (Coachman and Aagaard, 1988; see Section IV.E).

Estimates have been made from yearlong direct current measurements of the transports through the Straits of Gibraltar as discussed previously in this section. The details of the mixing and dynamics of the outflow as it comes into geostrophic adjustment and moves into the Atlantic as an intermediate layer were reported by Price et al. (1993).

The best direct estimate of mean mass transport by the ACC is 135 ± 10 Sv ($10^6 m^3/s$), based on four years of measurements, from Pacific to Atlantic through Drake Passage (Nowlin and Klinck, 1986). Estimates from large-scale ocean simulations may differ, e.g., the Fine Resolution Antarctic Model (Webb et al., 1991) gives a transport larger by 15-20%. Based on observations, short term changes of 30-50 Sv over two- to four-week periods have been observed (Whitworth, 1983; Whitworth and Peterson, 1985), and are principally barotropic in nature. At two distinct times, simultaneous current and property measurements at Drake Passage have enabled estimates of "instantaneous" transports by the ACC: 4 Sv fresh water, 6 and 8 x $10^{11}$ ml/s oxygen, 104 x $10^5$ gm/s silicate, and 14 and 11 x $10^{14}$ W heat (Guiffrida, 1985). Data do not exist to enable good estimation of variations of heat or fresh water transports by the ACC at Drake Passage or of any transport (even instantaneous) south of Africa or New Zealand/Australia.

There is an important Indonesian throughflow of water from the Pacific to the Indian Ocean. Its influence on near-surface properties is felt across much of the Indian Ocean and the freshwater budget could be sensitive to the throughflow rate. The throughflow rate is still a matter of research (Godfrey et al., 1995). Preliminary estimates from sections between Bali and Australia in 1989 and 1992 are that 20 x $10^6 m^3/s$ flows westward into the Indian Ocean. However, a considerable portion of this is recirculated water, and the net flow has been estimated at 12 ± 8 x $10^6 m^3/s$ (Fieux et al., 1992). Wyrtki (1987) believed this throughflow should respond to the monsoon, with a maximum in July-August and little flow in January-February. Kindle et al. (1987) forced a model with seasonal winds to generate an annual cycle of the throughflow with the same phase and a 5 Sv amplitude. Observations of this exchange are continuing and will do so as part of the WOCE Indian Ocean work (U.S. WOCE, 1993).

Fluxes via all these ports may vary significantly and somewhat interdependently because they are balanced by atmosphere-ocean exchanges. However, measurements of certain combinations would offer redundancy, and thus a check on the measurements. For example, net imbalances of volume inflow by the ACC to the Pacific Ocean greater than the Indonesian plus Bering Straits outflow, cannot exist over long periods (months).

At this time, we believe that we can monitor volume transport changes of the ACC south of the three major constricted areas; a long-term test is being made during WOCE. However, we do not now have the capability to monitor total volume transport or the transports of salt or fresh water with presently used methods. New approaches to such monitoring are needed. Research programs have demonstrated the feasibility of monitoring exchanges through the Bering Straits and the Straits of Gibraltar. Ongoing projects are attempting to estimate the Indonesian throughflow, rendered difficult because of the multiple narrow passages through which flow occurs.

Other circulation measures. In addition to property distributions, ocean modelers require measures of vertical structure of velocity and of eddy activity. This information is needed for data based models of circulation and property transports as well as for the validation of ocean and coupled models.

Estimates of eddy activity are attainable by satellite altimetry. Upper ocean measures of velocity were discussed in Sections IV.A and IV.C. Vertical structure of horizontal velocity can be obtained from hydrographic data (for geostrophic flow), moored time series measurements, or autonomous float measurements at one or more subsurface levels together with surface flow from altimetry and surface wind stress.

# V. ELEMENTS OF THE OCEAN OBSERVING SYSTEM FOR CLIMATE

By element is meant an instrument, platform, transmission system, or the processing required to observe a climate variable or quantifiable aspect of the climate system. In this section the OOSDP presents its recommended elements of the ocean observing system for climate. Initially, the observing system likely will be comprised only of elements (measurements/estimates) of existing "operational" systems plus a limited number of additions. Thus, we recommend an evolutionary development of the observing system; we believe this is realistic. The Panel has grouped its recommendations into four categories (Section III.A):

1) elements of existing "operational" systems;
2) elements to be added now to complete the initial observing system—either enhancements to existing operational systems or parts of existing research observing systems ready for conversion to operational status;
3) elements, perhaps not now readily obtainable, urgently required as enhancements to the initial system at the earliest feasible time; and
4) research and development likely to lead to further development of the system.

The Initial Observing System as defined by GCOS and in this document consists of specified elements of the existing operational systems and elements which should be added now. This initial observing system will constitute the first contribution to the common module of GOOS and GCOS. Implementation of this initial observing system as a smoothly functioning international system would constitute an important first pilot step toward establishing the complete global ocean observing system for climate.

Section IV has demonstrated that for many of the climate variables that must be measured by the observing system, our knowledge of the space and time scales of variability is rudimentary at best. In many cases, it is not yet possible to specify the sampling necessary to avoid aliasing. Thus, the available results of ongoing research programs are important in designing the observing system, and will continue to be so in the future. In addition, information provided from the system itself will be used in strategic planning and system evaluation (Section VII.E) which will continue to optimize the components of the observing system.

Table V.1 provides a list of the climate variables to be discussed in this section together with a pointer to the subsection where they are discussed. The general plan is to provide in each subsection a brief background for the elements and a rationale for pursuing each element as part of the observing system within the context of the goals set out in subsection III.C, and based on the scales of variability discussed in the previous section. Each subsection is then concluded with a list of recommendations designed to fulfill the requirements of the relevant subgoals.

General considerations. In addition to the characteristics of the fields to be measured and the capabilities of the available methods, design of an observing system should be guided by an understanding of what the system is expected to produce (the outcome). To some extent these expectations have been built into the goals of Section III. For the most part the recommended elements are aimed at providing global coverage, though for some regions, such as the Southern Ocean, the logistical constraints are prohibitive.

In principle, to capture the scales of variability identified in the previous Section IV, we must collect data adequate to provide field accuracies commensurate with the relevant climate signals. Generally, to properly characterize a climate field, sampling in space and time should be done about three to four times per decorrelation scale and period of both the energetic local signals (even if considered noise) and the desired climate-related signal. However, it is more realistic to design a system that has tolerable signal-to-noise ratios—accepting a degree of aliasing of high frequency variability into the climate signal.

## V. ELEMENTS OF THE OCEAN OBSERVING SYSTEM FOR CLIMATE

There is a generic need to have focused activities to bring together data from different sources (of the same type and of disparate types) for synthesis and progress toward improved processing and data quality. Section V.J describes the modeling elements of the observing system and how they might be utilized for this task. At a more fundamental level, and specifically for remote sensing, there must be a sustained focused effort to use different varieties of information for calibration and validation.

| SUBSECTION | CLIMATE VARIABLES | PRINCIPAL SUBGOALS |
|---|---|---|
| V.A | SST, SSS | 1a, 1c, 1d |
| V.B | surface wind | 1b, 1c, 1d, 2b, 2c, 3b |
| V.C | surface heat flux, surface water flux | 1c, 3b |
| V.D | heat and water transports and budgets | 1c, 3a, 3b |
| V.E | upper ocean T, S, and velocity | 2a, 2b, 2c, 3a, 3b |
| V.F | sea level | 2a, 2b, 3b, 3c |
| V.G | sea ice | 1e, 3a |
| V.H | carbon | 1d, 3a, 3b |
| V.I | water budget, heat content, time series, deep velocity | 3a, 3b |
| V.J | models | ALL |

Table V.1. Indication of climate variables discussed in each subsection of Section V together with the principal subgoals to which they contribute.

Measurement platforms. For proposed elements, we specify the measurement required for the observing system and offer possible existing measurement methods. The instrument platforms available include satellites, ships, moored surface and sub-surface buoys, drifting surface buoys, and autonomous floats and vehicles. Moored buoys and ships provide attractive platforms because they provide the means to make a direct measurement in situ, and because sensors and electronics can be recovered periodically for calibration. The pre- and post-calibration procedure, along with an understanding of sensor performance in the field, provide the methodology to maintain and quantify the accuracy of the measurements. Ships are attractive because they are manned and have power and because, in the case of the merchant ships, they can be cost-effective. Unfortunately, cost and logistics make it difficult to field and maintain dense sampling arrays of ships and moored buoys on a global basis. Drifting surface buoys and subsurface floats offer the only practical possibility of obtaining in situ data in remote, data sparse regions.

*Satellite methods* provide large scale coverage for some variables. Resolution of diurnal variability and global coverage is possible using five geostationary satellites (used for weather observations) and one or two polar orbiting satellites (Rossow and Schiffer, 1991). The disadvantages are that, for most variables, considerable care and substantial in situ resources are required to ground truth the remotely-sensed data, to verify sensor calibration, and to correct the data quality problems associated with looking at the sea surface through the atmosphere.

*Surface moorings* provide a platform for observation of upper ocean variability, air-sea interactions and variables useful for weather prediction. Surface buoys can be equipped with meteorological packages for measuring parameters involved in air-sea heat, mass, gas, and momentum exchange. Real-time telemetry is possible from remote oceanic locations via communications satellites. Surface moorings generally have a shorter design lifetime than subsurface moorings because of either mechanical wear, corrosion, biofouling in the euphotic zone, or vandalism. However with telemetering surface buoys, loss of data is minimized should the mooring itself be lost. The TAO array of moorings deployed in the equatorial Pacific (Hayes et al., 1991; McPhaden, 1993) provide an example of a large scale surface mooring array. For long-term moorings in extra-tropical regions, more robust mooring hardware is required. Surface moorings using 3 m diameter discus buoys have been used by the U.S. National Data Buoy Center (NDBC), the U.S. Coast Guard, and in research programs at various locations around the world, including one installation at 60°N, 20°W for the summer of 1991.

*Sub-surface moorings.* Mooring location, design and instrumentation depends on the scientific questions being addressed. For instance, the use of subsurface moorings is generally favored for the study of the circulation of deep and intermediate waters. In WOCE, arrays of subsurface current meter moorings are being deployed to determine the flow at certain points in the general circulation (e.g., deep western boundary currents along New Zealand in the South Pacific and across the Indian Ocean at 20°S). Subsurface moorings may also be favored over surface moorings where environmental conditions are too harsh for the survivability of a surface mooring; for example, in polar latitudes where ice floes may be a problem, in regions of extreme wave heights or near surface current shears, etc. Similarly, deployment of subsurface moorings in the deep ocean may be preferred in order to minimize the potential damage due to vandalism as, for example, by fishing fleets (though subsurface moorings are not immune to such damage, particularly in shallow water). Subsurface moorings may also be expected to have a longer design lifetime than for a surface mooring at the same location because the interior ocean is colder and less energetic which implies less mechanical wear and corrosion for mooring hardware and instrumentation. Maintenance of a moored array using conventional mooring technology requires dedicated ships of sufficient size and capabilities for recovery and deployment operations. Subsurface mooring deployments of up to two years long are now common in the deep ocean.

*Ships* that might be used as a component of the observing system include research ships, military vessels, weather ships, and merchant ships. Research ships of various academic and government institutions, including polar supply ships and ice-breakers, are attractive platforms because they often go to data-sparse regions and have an interest in collecting high quality surface observations. The total number is, however, very small. Military vessels are also attractive because they also often go into data-sparse regions and travel routes other than shipping lanes. It is unknown whether or not they would support near-real-time transmission of their data and location and how difficult they would be to instrument.

Only two weather ships remain in service, one south of Iceland (59°N, 20°W) operated by the United Kingdom (UK) and one at 66°N, 02°E operated by Norway. Over the years, the long-running high quality time series of data collected on the weather ships have contributed much to our understanding of the variability of the surface and the air-sea fluxes, and to the development of various bulk formulae for the fluxes. Light ships and coastal navigational platforms can be outfitted to record surface data and can be a valuable source of coastal data.

At present the bulk of surface reports come from the VOS of the WWW system. About 7000 ships from 49 countries now participate. One problem associated with VOS is the relatively low quality of their instruments and uncertainties in the measurements associated with the equipment and the observers. A selected subset of 46 VOS in the North Atlantic were recently studied during the VOS Special Observing Project–North Atlantic (VSOP-NA) in order to identify and quantify biases in VOS data (Kent and Taylor, 1991; Kent et al., 1993). The results showed that, not only was there room for improvement in the measurements made on the VOS, but also that, given a good understanding of the VOS data and the specifics of how it was collected, it was already of sufficient quality to suggest that some of the differences discovered during model-data comparisons were attributable to deficiencies in the atmospheric forecast model. VOS are also a key part of the upper ocean sampling program.

*Subsurface floats* have been used for three decades to measure currents at a predetermined depth or pressure. Since 1990 a new type of float has been in use by WOCE. This instrument regularly ascends to the surface and transmits its data via satellite before returning to its drift depth. The goal of WOCE is to maintain, on average, one float in each 5° square for five years. Recently these floats have been developed to measure vertical profiles of temperature on ascent; salinity profiling is in the advanced development stage.

*Drifting surface buoys* have been deployed for a number of years. For naval applications there are air-deployable, "mini-drifter" buoys that have a life of approximately 90 days and can telemeter data back via Service Argos. Research buoys have been designed to have longer (up to 18 months) life. Drifting buoys collect in convergences (associated with Langmuir cells, fronts, and other ocean currents) and thus may provide a biased sampling of some properties. This requires reseeding or redeployment of additional drifters in order to maintain spatially uniform coverage. The WOCE Surface Velocity Program (WCRP, 1988a, b) has chosen initially a sampling resolution of 500 km x 500 km globally for surface velocity. This requires a continuous array of about 1100 drifters with 225 drifters in the Atlantic Ocean, 495 in the Pacific Ocean, 180 in the Indian Ocean, and 200 in the Southern Ocean (defined as south of 40°S). The number of drifters required for seeding each year depends strongly on the half-life. The TOGA Pan-Pacific Surface Current Study is deploying drifters within 15°N and 15°S and between 80°W and 126°E; this requires 230 drifters every 18 months. At present over 600 drifting buoys transmit data on the GTS with several thousand reports per day.

Telemetry. Some of the telemetry deficiencies have been mitigated since 1990. Argos system saturation is no longer the problem it was, although its data-rates are still restricted and two-way capability is just being discussed. For certain observations, data returns will be constrained by capabilities of the Argos system, even in its planned enhanced versions. Costs are an issue with Argos as well as with some other telemetry systems. Argos has been the valuable workhorse of the oceanographic community for over a decade; it is clearly one of the technologies upon which the observing system is built. It, and systems that are even more capable, are essential in the future.

## V.A. Sea Surface Temperature and Sea Surface Salinity

### V.A.1. SST measurement methods

The surface sensible and latent heat flux and the net longwave flux depend upon the ocean skin temperature which is typically a few tenths of a degree colder than the near surface sea temperature measured within a few centimeters of the surface. The near surface temperature is equal to the bulk mixed layer temperature (measured at a depth of a few meters) except during periods when a diurnal thermocline exists. Near surface diurnal thermoclines form through solar heating of the upper ocean on very calm days (winds < 3 m/s); SST increases of a few degrees can occur. This report assumes that, for climate purposes, it is the near surface or bulk temperature which is required. That is because flux determination formulae are defined in terms of the bulk SST. Also, because the departure of the skin temperature from the near surface sea temperature varies on the short time scale of the surface flux variations, it is more convenient to define the near surface temperature as the SST and consider the skin temperature to be an internal parameter within the surface transfer process.

Satellites. The NOAA series of satellites carries the Advanced Very High Resolution Radiometer (AVHRR). AVHRR provides SST with as good as 1.4 km resolution in cloud free areas. The satellite sensor itself is sensitive to about 0.1°C, but this is degraded by uncertainties associated with the propagation of the radiation through the earth's atmosphere (Minnett, 1990). In practice the accuracy achieved varies with time and place. Typically, the AVHRR data is accurate to approximately 1.0°C if no dust or aerosol related problems interfere. Accuracy can be improved to about 0.5°C with local calibration against in situ measurements (Stramma et al., 1986) which would remove regional and seasonal variability found in the atmosphere (Minnett, 1990). According to Large (1985), AVHRR has a global rms error of approximately 0.7°C in monthly averages with the largest errors in some regions reaching 2°C.

Compositing of images close in time allows images of larger cloud free areas to be constructed under the assumption that advection and local change in the ocean are small. Unfortunately, many areas of the globe that are critical for weather and climate problems (such as near Greenland, Iceland, and Scandinavia) have such persistent cloud cover that cloud-free images are so rare that even compositing is of little help. A further problem in compositing images is short time-scale SST variability due to near surface diurnal thermoclines and variations in the surface skin effect. Bates and Diaz (1991) compared 6 years (1982-1988) of satellite multi-channel SST (MCSST) data with ship and buoy data; they found the MCSST SSTs cooler in the mean (by 0.18°C to 0.64°C) than the in situ data. Calibration of AVHRR at night and use of in situ buoy data together with a model for the differences between skin and bulk temperatures may result in improved accuracy (Schluessel et al., 1990).

Combinations of microwave and infrared sensors may reduce sensitivity to clouds and aerosols. Schluessel et al. (1987) discuss improvements in the accuracy of AVHRR-derived SSTs by using additional data from TOVS (television infrared observing satellite (TIROS) operational vertical sounder) or high-resolution infrared sounder (HIRS). HIRS data was useful in reducing biases associated with atmospheric water vapor and temperature, improving rms accuracies from 0.9°C to 0.3°C. The infrared Along-Track Scanning Radiometer (ATSR) on ERS-1 has on board calibration and a dual-look to allow the effects of the atmosphere to be removed from the signal. Unfortunately, it has a narrow swath compared to AVHRR which limits the number of cloud free views of the surface obtained. However, ATSR could be valuable for calibration of AVHRR as more ATSR data becomes available.

Passive microwave sensors (such as the Scanning Multi-channel Microwave Radiometer (SMMR)) are sometimes suggested as a means of overcoming atmospheric transmission problems to determine SST. However, such sensors are less accurate than infrared techniques and have been found to have drift and bias problems. Partly this is due to the varying microwave emissivity of the sea surface. Acceptable accuracy (see Section IV.A) for SST estimation has not been achieved. Sea surface temperature estimates can also be developed hourly at approximately 15 km resolution from the Vertical Atmospheric Sounder on geostationary satellites; the accuracy of this method is not yet fully documented.

Satellite remote sensing methods for SST require a well-supported, parallel program of in situ measurements both for the calibration and validation of sensors and existing algorithms, and for the development of improved algorithms that will deliver increased accuracy of measurement. For example, Cornillon (1989) reported that improvements to the satellite SST products now available could be had through changes made to the archived data to include radiances from all channels of the HIRS. In addition, he recommended research into the physics associated with the difference between skin and bulk SSTs, the use of additional spectral channels from other sensors, limb darkening due to increased optical thickness at the periphery of the scan, and improved sensor calibration before flight and during the flight.

Surface moorings can, with care, measure both the near-surface temperature (beneath the surface skin) and the bulk mixed layer temperature. Thus, errors due to diurnal thermoclines can be avoided. The near surface temperature measurement requires a near-surface or floating array properly shielded from direct sunlight. The bulk surface temperature is easily measured with a sensor on the mooring line at the desired depth. Temperature measurements can be made very near the surface by buoyant thermistor chains and below by attaching instruments to the buoy and mooring line.

Temperature sensors and related electronics can be made that achieve accuracies of 0.005-0.010°C during calibrations in laboratory conditions (Weller et al., 1990). Diurnal change in stratification of the upper ocean and solar heating of the buoy, as mentioned above, can introduce larger errors, as can deficiencies in the sensors and electronics used. In practice, the difficulty of placing the temperature sensor near the surface while at the same time preventing it from being exposed to the air introduces errors associated with shallow stratification of order 0.1°C. Some one hundred buoys are maintained world-wide (Regular Information Service Bulletin on Non-drifting ODAS, August 1993; IOC, 1991) with additional buoys deployed as part of research programs.

For research ships, SST measurement methods include trailed thermistors, pumped thermosalinographs and SST radiometers. However, the use of infrared radiometers on ships to measure skin temperature requires care and attention to calibration at a level that make it not feasible for wide-spread implementation (Schluessel et al., 1990).

Merchant ships estimate SST from engine room intake readings, buckets, and hull contact sensors. For the VOS ships, hull-mounted temperature sensors appear to be a good solution because of the relative accuracy and ease of use as demonstrated by the VSOP-NA program (Kent and Taylor, 1991; Kent et al., 1991). Engine intake data showed greater scatter, large consistent biases on some ships, and a mean bias of about +0.3°C. Mean bucket-derived data were up to 0.5°C warmer in low heat flux, stable, and strong sun conditions, but otherwise gave results comparable to hull sensors. In previous studies biases were found between engine intake and bucket of up to 1°C with seasonal variability in the error (Parker, 1985; Taylor, 1985). However, in the mean, Wilkerson and Earle (1990) report that ship sea temperatures were only 0.1°C higher than the respective buoy measurements.

Drifting surface buoys can give very good SST data; typically an accuracy of ±0.1°C and a drift of less than 0.1°C in a year. Of the various common technologies for measuring SST, drifting buoys do the best job of placing the sensor near the sea surface.

V.A.2. SSS measurement methods

The measurement of salinity has become more routine in recent years due to the development of compact, stable conductivity sensors. It is now possible to obtain surface salinity records from shipboard thermosalinographs and long-term records from moorings or drifting buoys. In addition, expendable and autonomous profilers are now available for subsurface salinity profiling. Finally, remote sensing techniques have been proposed. These approaches are discussed below.

Moored salinity measurements. McPhaden et al. (1990) have successfully deployed conductivity-temperature recorders on upper ocean moorings in the Equatorial Pacific for periods of six to seven months.

Drifting salinity measurements. Conductivity sensors are being deployed on surface drifters with good preliminary results.

Thermosalinographs. Somewhat trouble-prone in the past, there is reason to believe that new instrumentation and a systematic approach to deployment on the VOS will yield a valuable enhancement of surface salinity data. A NOAA/National Ocean Service (NOS)-Woods Hole Oceanographic Institution (WHOI) pilot project is currently underway.

Retrievable CTD. Small CTD packages with internal recording could be developed for easy deployment on light line and retrieved, much like the mechanical bathythermograph. This would allow inexpensive CTD profiles to be obtained from a moving ship. A proof of concept has been done by N. Brown and A. Fougere at Woods Hole.

Remote Sensing. Low frequency microwave emissions vary weakly with SSS, however, there is poor spatial resolution unless a very large antenna is used. Synthetic enlargement of antennas may be possible, but it seems that sensitivities of only one unit in salinity might be achievable. Since the signals of interest are at least an order of magnitude smaller, and have very small spatial scales, the technique does not look promising at this time. However, continued study may be warranted.

V.A.3. Observing system requirements for SST and SSS

SST is one surface variable for which established global products already exist. The NMC experience gained in developing such a product has generally confirmed the discussion above. For example, they have found:

- that ship data, as presently available, is accurate to about 1.5°C (standard deviation). For equatorial and southern ocean areas the ship data is too sparse for constructing maps of SST.
- AVHRR retrievals can have biases of 1° to 3°C caused by changing aerosol content of the atmosphere, otherwise the accuracy is about 0.5°C (day) or 0.3°C (night) standard deviation.
- the most reliable SST data comes from drifting and moored buoys (standard deviation 0.5°C); however these data are much too sparse to be used alone.

The present NMC product uses the buoy and ship data to remove biases and trends from the AVHRR data (Reynolds and Smith, 1994). The smaller scale variations of the SST field are established from the AVHRR data and an optimal interpolation technique used to blend all the data into an SST map. Based on the error spatial correlation scale of the AVHRR retrievals, NMC estimates that roughly one in situ device is needed in every 5° square on several day time scales to correct the AVHRR data. In some places a denser buoy network is required, in others high quality VOS could be used. At present the Southern Ocean is particularly in need of more high quality SST measurements. These in situ high quality observations should have a mean bias within 0.1°C to allow production of a global SST field to meet the needs of the observing system (area and space averaged SST to accuracy of a few tenths °C, see Section IV.A).

In contrast to SST, systematic measurements of surface salinity are a new but feasible undertaking for the observing system. Such measurements would go far toward improving our understanding of the global freshwater cycle and providing information on buoyancy forcing of ocean circulation, related to modification of surface waters and formation of subsurface water masses.

RECOMMENDATIONS FOR V.A

Three existing elements are recommended to continue the production of present SST products derived from satellite AVHRR, with in situ data used for calibration. The additional elements recommended for the initial system are required to improve accuracy and coverage. For example, the use of ATSR would complement the present AVHRR because of its reduced sensitivity to error from atmospheric variability (for example, aerosols). VOS and drifter observations are required to achieve one in situ measurement on weekly or monthly basis per 500 km by 500 km square with a mean bias within 0.1°C (see Section IV.A.3 for details). These elements support subgoal 1a, are required for subgoals 1b and 1c and contribute to subgoals 1d, 2a, 2b, 2c, 3a, and 3b. Enhancements to the initial system address coverage for SST in cloudy regions and move towards obtaining operational SSS.

The recommendations for SST and SSS are:

Elements of existing observing systems:
A1. Global satellite measurement of SST using AVHRR.
A2. Moored and drifting buoy network measuring and reporting SST.
A3. VOS fleet measuring and reporting SST.

Elements to be added now to complete the initial observing system:
A4. Use of ATSR in conjunction with AVHRR to improve SST data by providing an estimate of atmospheric aerosol and allowing removal of atmospheric transmission effects.
A5. A subset of the existing VOS, research fleet, polar supply/ice breaking ships fitted with improved (hull contact) sensors. These might also be equipped to report position and SST automatically.
A6. Additional drifting buoys deployed in regions lacking VOS data, especially the Southern Ocean, Indian Ocean, northern North Atlantic, and northern North Pacific.
A7. Since the needs for SST data for climate purposes are not identical to those for weather forecasting, a dialog must be established between those seeking surface temperature data for the observing system and those planning future satellite sensors and platforms in order to ensure that there be both continuity of coverage and use of appropriate sensors and sampling schemes.
A8. Maintenance and augmentation of conductivity and temperature measurements from moorings, such as have been obtained from selected TAO moorings since 1987.

Enhancements to initial system:
A9. Increased density of in situ measurements to provide SST with sufficient accuracy and spatial resolution in regions where satellite measurements are inadequate to provide basic coverage due to cloud cover or other problems.
A10. Development of the operational use of thermosalinographs on VOS and conductivity sensors on drifting buoys.

Research and development:
A11. Continued improvement of the accuracy of satellite SST measurements should be sought by calibration using the in situ measurements taking into account the ocean surface skin effect, by archiving the raw satellite data, and by improvements to the algorithms relating the raw measurements to SST.

A12. Satellite data relay systems should be improved to allow more surface platforms to report SST data more often and at lower cost.
A13. Assess the feasibility of estimating sea surface salinity using satellite observations.

## V.B. Surface Wind Velocity and Wind Stress

### V.B.1. Measurement techniques

Sea surface wind data may be obtained from ships, moored and drifting buoys and satellites. Each platform type produces data with different error characteristics and there is no good absolute calibration standard available, except perhaps the anemometer-based, weather ship observations.

The Voluntary Observing Ships estimate wind velocity using visual estimates, hand-held anemometers, or fixed anemometers. *Visual estimates* imply the use of a conversion scale to relate the observed sea state to a wind speed. Different versions of this "Beaufort scale" have been proposed in attempting to make visual wind observations agree with anemometer derived data (e.g., Cardone et al., 1990). Other corrections may be necessary; for example, there is evidence that visual observations at night may be biased low at higher wind speeds (Kent et al., 1991). *Anemometer-derived wind observations* suffer from errors due to poor exposure and air-flow disturbance by the ship. Errors also occur in visually averaging the anemometer reading, and in converting relative wind observations to true wind by subtracting the ship velocity. *Hand-held anemometers* give very scattered estimates of wind speed particularly above 15 knots and also wind directions with greater scatter than from visual or fixed anemometer methods.

Research Ships (and special ships such as Antarctic supply vessels, etc.) can provide high quality wind observations using anemometers mounted on special booms or masts. Without using a boom, but with attention to the flow distortion caused by the ship, Queffeulou (1991) achieved good agreement (standard deviations of 0.4 m/s and 5° in wind speed and direction differences, respectively) between two independent systems mounted on the same ship. However, unless corrections for flow distortion are applied, biases of around 5% may occur even for well exposed anemometers (e.g., Yelland et al., 1994). The availability of relatively cheap fast response wind sensors and microcomputer systems has lead to the development of instrument systems for routinely estimating the wind stress using the inertial dissipation method (e.g., Large and Businger, 1988). There is evidence (Edson et al., 1991; Yelland et al., 1994) that this method is much less susceptible to errors due to wind flow distortion by the ship than the bulk method. In the future routine estimates of wind stress might thus be obtained both from Research and merchant ships.

Moored instrumented buoys can be used to measure wind velocity using anemometer, wind vane, and compass systems. Although air-flow disturbance by the buoy can normally be made negligible, the low anemometer height on many buoy systems suggests that there is a risk of sheltering and unrepresentative wind measurements at high wind and sea states. An alternative measurement method from moorings uses the ambient noise in the ocean to estimate the wind speed or magnitude of the wind stress. Directional information is not available by this technique, and it has had only limited use and testing. However Vagle et al. (1991) found that, away from coastal areas, the Weather Observations Through Ambient Noise (WOTAN) technique provided wind speed good to an accuracy of 0.5 m/s in comparison with moored instrumented, surface buoys.

Most free drifting surface buoys are designed to be current followers with drogues and minimal surface expression. These are not suitable for wind estimation (except perhaps using the ambient noise technique). Air-sea interaction or flux drifters do not attempt to follow the water and thus can have a larger above water structure, permitting more complete meteorological measurements including wind velocity. However, the extra sensors significantly increase the cost of what is normally considered an expendable system. Anemometer heights on drifting buoys are likely to be similar or lower than those for moored buoys with similar sheltering errors in high sea states.

Satellite instruments include scatterometers, altimeters, and passive microwave radiometers. Scatterometers provide a measure of the radar backscatter from the surface, which in turn is used to infer vector wind speed or stress. Scatterometer wind speed accuracy may approach 1 m/s, though the algorithms for converting backscatter to wind speed and to wind stress remain the subject of ongoing research. A scatterometer has been flown on ERS-1 and another is planned for the Japanese Advanced Earth Observing Satellite (ADEOS). The instrument specifications suggest rms accuracy of 2 m/s or 10% in wind speed and 20° in wind direction for the wind speed range 2 to 30 m/s. Spatial sampling is of order 25 to 50 km. The ERS-1 scatterometer views to one side of the spacecraft only and does not provide a complete duty cycle. For the NASA scatterometer (NSCAT) on ADEOS, which views both sides, the orbital path will yield 375 km gaps between swaths of data; successive orbits will fill the gaps and a global map could be produced every three days (Kelly and Caruso, 1990). Microwave wind scatterometers allow determination of the wind vector with an ambiguity of 180° on the direction of the vector and some residual uncertainty of the order of 5 to 10°. The ambiguity may be removed by a wind field analysis process, based on consistency with neighboring wind data. This process is greatly facilitated (and made automatic) when a good-quality first-guess field is used (as done routinely by operational meteorological centers). Algorithm development in conjunction with ground truthing is needed to improve accuracy.

Altimeters and microwave radiometers provide wind speed information only. Altimeters on satellites provide a measure of wind speed with an accuracy of 1 to 2 m/s but sampling is limited to the sub-satellite track. Passive microwave sensors such as the special sensor microwave/imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP) spacecraft can be used to obtain wind speed data over a wide swath. Data from the SSM/I sensor was compared to buoy data by Goodberlet et al. (1989); with some work on the wind algorithm, approximately 85% of the data on any given day had an accuracy of ±2 m/s.

Satellite measurements will require in situ supporting measurements. For example, for the scatterometer, Ezraty (1989) recommends both an initial calibration/validation exercise to tune the algorithm relating backscatter to wind speed (or stress) and long-term monitoring to detect instrument drift and problems in the algorithm chosen after the initial calibration/validation. The initial calibration/validation should be three to four months in duration; the long-term monitoring should be for the life of the remote sensor. According to Ezraty an array of five equally spaced (125 km) surface buoys with in situ wind measurements provided a good balance between cost (number of buoys) and ability of the array to calibrate the scatterometer. Validation might be performed by comparison with existing ship or buoy data.

### V.B.2. Observing system requirements for wind velocity and wind stress

The wind stress is required for forcing ocean models and estimating air sea fluxes. The stress represents the vertical flux of momentum, and the scalar fluxes (humidity, heat, gas transfers) are also related to the wind speed. However, present observation systems determine, or are calibrated in terms of, the wind velocity. The relationship between wind stress and wind speed depends inter alia on the roughness of the sea surface, which raises the question of whether wave observations must be made by the observing system. At the simplest level, the wind stress can be determined from the wind velocity using a bulk formula in which the drag coefficient is a simple function of the wind speed and standard stability corrections are applied. This approach is appropriate to the conditions under which the drag coefficient value was determined. Thus, open ocean determined drag coefficients are taken to be applicable to well developed sea states, regions of "old wave age". In shallow water or fetch limited areas, the waves are young and a higher drag coefficient, and hence wind stress, values are expected. Models of wave-induced momentum transfer (Janssen,

1989) have demonstrated skill both in calculating the wind stress and in forecasting wave fields, and the accuracy of wave forecasts has been suggested as a sensitive test of the accuracy of the wind field analysis.

Over the open ocean, the degree to which non-equilibrium sea state conditions influence the wind stress and scalar fluxes is not presently known. For the purposes of this report it will be assumed that sea state and wave climate will be observed and forecast for other components of the GOOS (for example for ship routing and marine structures). It also will be assumed that, should it prove necessary for attaining the desired flux accuracy, the specification of the sea state can be obtained by running a wave forecast model in conjunction with an atmospheric forecast model. With this proviso, observations of the wind velocity and wind stress can be considered equivalent provided that an estimate of the atmospheric stability is available.

It is expected that, in future, the observing system requirements for surface wind velocity (or wind stress) data would be satisfied by two or more operational polar orbiting satellites each carrying double sided scatterometer systems. However, to date no operational scatterometer system has been flown and the full potential of scatterometer data has yet to be realized. Thus, there remains a need for good in situ wind observations. It is also expected that there will be a continuing need for independent wind data to calibrate and validate the scatterometer systems.

As a source of in situ data, the TOGA TAO moored buoy array provides wind measurements for the tropical Pacific and similar arrays in other tropical oceans have been suggested. However, extension of moored buoy arrays to cover the global ocean is not likely to be practicable. It also seems unlikely that drifting buoys will provide significant quantities of wind data unless the ambient noise method (or other new techniques) is developed to an operational state.

Ship wind observations are the basis of our existing wind velocity climatology over the ocean. These observations should be continued to ensure that future climatologies which use satellite, buoy, or other data are consistent with past climatological data. In this respect it might be argued that every effort be made to continue to obtain the wind data as it has been obtained in the past. However, it must be recognized that the characteristics of the ship data have changed and will continue to change. The typical size of ships has increased (with the possible result of changes in visual wind estimates), more ships carry anemometers, and ship navigation has become more precise. Given these unavoidable changes, and since the ship data may need to be used to verify satellite wind estimates and for assimilation into forecasting models, improvements of the present accuracy of ship wind data are desirable.

An alternative source of surface wind information is from NWP models. For this approach the observing system requirements are to provide the data which, through assimilation into the models, will improve the estimates of the surface winds and also to obtain data to verify those estimates on a continuing basis. Ocean surface data most useful in this approach are SST (Section V.A), surface wind observations, and surface pressure. Surface pressure observations can be obtained from drifting buoys that are unsuitable for providing direct wind estimates.

With regard to the desirable accuracy of wind observations, any simple quantitative statements must be treated with caution since the desired accuracy will vary significantly from one application to another. However, to give a rough indication of the level of accuracy likely to be needed WOCE may be used as an example. WOCE has been organized in three core projects. For Core Project 1, the Global Description of the Ocean Circulation, and Core Project 2 , Southern Ocean research, the flux data requirements were defined (WCRP, 1986, 1988c) in terms of the mean values for one month periods and areas of say 2° latitude x 5° longitude. The desired accuracies were stated (on the basis of fairly crude arguments) as 5 to 10% of direction for wind velocity, the larger of 10% or 0.5 to 1 m/s for wind speed, and the larger of 10% or 0.01 N/m$^2$ for wind stress. For TOGA the requirements have been given for 30-day resolution in an area of 2° latitude by 10° longitude as

0.5 m/s for wind speed and 0.01 $N/m^2$ for wind stress (WCRP, 1992). It should be noted that, where mean values are specified as the required product, an estimate of the variance of that quantity would also be desirable.

RECOMMENDATIONS FOR V.B

The existing elements that now produce surface winds (e.g., NWP models, VOS observations, and satellite scatterometers) must continue. Continuation of the TAO array is required to support subgoal 2b. More sea level atmospheric pressure measurements and improved VOS observations will lead to improved ability to obtain global wind and wind stress fields. There should be a commitment to continued, improved satellite scatterometry. Continued improvements to in situ measurement of wind and stress are also recommended. The recommended elements are directly in support of subgoal 1b and achievement of this subgoal is required for subgoals 1c, 1d, 2b, 2c, and 3b.

Elements of existing observing systems:
B1. NWP surface wind field analyses.
B2. Meteorological observations from VOS.
B3. Sea level pressure measurements from buoys.

Elements to be added now to complete the initial observing system:
B4. Continued development of a fully operational satellite scatterometer system. A dual swath scatterometer to be flown on each of two polar orbiting satellites with an adequate ground segment for data processing and an established scheme for calibration and verification of the data (possibly requiring the implementation of buoy arrays for satellite calibration).
B5. Continuation of the TAO array in the Pacific, which is particularly important for tropical wind measurement.
B6. Increased number of buoys reporting sea level pressure, especially in the Southern Hemisphere.
B7. Implementation of simple measures to improve VOS wind data. Provision to ships' officers of a method of reliably calculating true wind from relative wind. Correction of anemometer winds for the instrument height. Phased out use of handheld anemometers.

Enhancements to initial system:
B8. Depending on the success of implementing an operational scatterometer wind system, consider the need to implement more accurate wind or wind stress measurements on a subset of the VOS. Possible methods would be:
- Automatic averaging of anemometer derived winds and integration of the ships' global positioning system (GPS) navigation data (position, speed and direction) into the data set to improve the quality of absolute wind measurements. The latter would allow the ship's velocity at the time of wind measurement to be accurately used in calculating the true wind.
- Implementation of stress estimation using the inertial dissipation technique on a substantial subset of the VOS.

Research and development:
B9. Assessment of the need for expansion of the TAO array into the Atlantic and Indian Oceans.

## V.C. Surface Heat and Freshwater Fluxes

### V.C.1. Measurement techniques for surface heat flux

The surface heat flux consists of the turbulent fluxes of sensible and latent heat, and the net shortwave and longwave radiative fluxes. Different measurement techniques are used for the turbulent fluxes compared to the radiative fluxes. However, as discussed below, it is expected that residual biases in the heat flux estimates will have to be removed by using estimates of the total surface heat budget, therefore this section will discuss all the heat flux components.

Sensible and Latent Heat. Direct estimation of the turbulent heat fluxes, for example using the eddy correlation technique, has proved difficult to perform even given the controlled conditions of a research ship or platform during the relatively short period of an air-sea interaction experiment. It is therefore expected that in situ flux determinations will be based on the bulk aerodynamic parameterization schemes which express the turbulent fluxes in terms of the basic meteorological variables (air pressure, temperature, and humidity, wind speed, SST). These variables can be measured on ships (VOS and research ships) and on moored buoys. The VOS data requires improvement; the present errors together with methods for increasing the accuracy of the VOS observations were discussed by Kent et al. (1993) and implementation of those and similar measures is recommended. Air-sea interaction or flux drifting buoys have been designed but the cost of these is probably prohibitive for deployment in great numbers. Satellite instruments can measure the SST (Section V.A) and the surface wind speed (Section V.B) but cannot provide estimates of the near surface air temperature for sensible heat flux determination. Estimates of the monthly mean near surface humidity have been made using satellite microwave radiometers assuming a link between column integrated total water vapor and the near-surface humidity (Liu, 1988). Historical radiosonde data are used to develop an empirical relation. Used together with estimates of wind speed in the bulk formula, these humidity estimates may give monthly mean latent heat fluxes to an accuracy of 20 W/m$^2$ (Liu and Niiler, 1984). Work on the technique continues, and Schulz et al. (1993) have claimed improved accuracy using data from the SSM/I. The success of such schemes depends on the extent that the boundary layer structure is constrained by the large scale flow and SST. Indeed it has been suggested that a surface heat flux climatology (at least for the tropical Pacific) can be determined from SST and wind data alone (Seager et al., 1988; Seager and Blumenthal, 1994) using a model similar to that of Liu and Niiler. A problem with these techniques is that errors are introduced by calculating monthly mean fluxes from monthly mean surface data and neglecting correlation terms which may vary both with position and season (Gulev, 1994; Josey et al., 1994).

Radiation measurements are not presently obtained from VOS. Climatological calculations of the radiative fluxes depend on observations of cloud type and amount which are of dubious accuracy. Katsaros (1990) has reviewed the parameterization models available and found mean daily errors of order 10 to 20 W/m$^2$ for the shortwave insolation and order 0 to 10 W/m$^2$ for longwave irradiance. These estimates were based on research ship observations. Incoming shortwave and longwave radiation measurements can be made from ships if the sensors are gimbaled, protected from soot and spray, out of shadows, and high enough not to see the heat from the ship and exhaust stack. On many ships these requirements may be impossible. However, one advantage of a ship installation is that the radiometers can be periodically cleaned. Research ships with special booms are required to measure outgoing shortwave and longwave radiation, thus giving net shortwave and net longwave radiation, the albedo, and the surface emissivity for longwave radiation. Given knowledge of the albedo and emissivity, the reflected shortwave can be estimated from the insolation and the outward longwave calculated from the SST. Surface buoys can be equipped with incoming shortwave and longwave radiation sensors. For best accuracy, these should be gimbaled. The shortwave measurement has been made with accuracy of approximately 5% (Weller et al., 1990). However, because longwave sensors are more affected by spray, condensation and other contamination of the hemispherical dome covering the thermopile, the accuracy and feasibility of long term unattended incoming longwave radiation measurements is less certain.

Satellites provide estimates of the radiative heat fluxes. Incoming shortwave can be estimated from GOES visible imagery, providing maps every day to an accuracy of 10 - 20 W/m$^2$ (Gautier et al., 1980). Chertok (1989), using NIMBUS 7, produced monthly mean solar irradiance for 9° x 9°

areas over the ocean with an error estimated to be 10 to 20 $W/m^2$. Bishop and Rossow (1991) discuss a recent method for computing the clear sky solar irradiance; this method requires knowledge of various quantities, including solar zenith angle, atmospheric ozone column abundance, atmospheric temperature-humidity profiles, tropopause temperature and pressure, surface pressure, surface temperature, surface reflectance of visible light (albedo), cloud amount (fractional coverage), cloud optical thickness, cloud top temperature and pressure, and surface type (ocean, land, coast, ice). Some of this data comes from the TOVS. The computational method was checked against data taken from Ocean Weather Stations for several months in 1983 and 1984; their computationally fast (compared to more complex radiative transfer models) algorithm did better in determining the shortwave radiation (mean bias of -2 $W/m^2$) than bulk formulae proposed by Budyko (1963) (mean bias of -42 $W/m^2$), Reed (1977) (mean bias of 10 $W/m^2$), and Dobson and Smith (1988) (mean bias of 18 $W/m^2$).

Much of the cloud-related satellite data is being collected by the International Satellite Cloud Climatology Project (ISCCP), part of the WCRP (Rossow and Schiffer, 1991). ISCCP data is available every three hours on a 280 km grid. Shortwave radiation estimation using the Pinker and Laszlo (1992) algorithm has shown residual matching errors with the basic surface radiation network well below 10 $W/m^2$ for mean monthly 2.5° x 2.5° area averaged values. Li et al. (1993) derived an algorithm to calculate net shortwave at the surface from satellite shortwave at the top of the atmosphere. The algorithm requires column integrated water vapor and the solar zenith angle; the results agreed with data from land-based towers to approximately 2 $W/m^2$. However, given the difficulty in making accurate in situ estimates of net shortwave radiation at sea and the sparsity of radiation data from the sea surface, further work should be done to assess the accuracy of these estimates over the ocean's surface. There may be a limit to which single point ground truth stations can be used to calibrate satellite measurements of shortwave radiation. Pinker and Laszlo (1991) attribute some of the difference they find between remotely-sensed shortwave and ground station data to the different spatial and temporal averaging associated with each method. When incoming shortwave data is determined, computation of net shortwave still relies on knowledge of appropriate values for the albedo, and this data may need improvement.

Satellite methods for estimating incoming longwave radiation are considered to give maps with an accuracy of 20-40 $W/m^2$ (Frouin et al., 1988) using data from geostationary satellites. Longwave radiation estimates from the ISCCP based on Gupta et al. (1992) are expected to have an error below 20 $W/m^2$.

NWP models, atmospheric general circulation models, and coupled ocean-atmosphere models can also be used to produce estimates of the surface shortwave and longwave radiation. Such models, because they represent the atmosphere as a finite number of discrete levels, cannot implement the most sophisticated algorithms (called line-by-line codes because they compute transfer of radiation through the atmosphere frequency by frequency for many discrete frequencies) for computing radiation at the surface from the radiation known to be available at the top of the atmosphere. Models with discrete levels in the atmosphere cannot accurately replicate the cloud types and amounts that are observed; nor can they correctly represent the thickness of observed cloud layers. Comparison of NWP model radiative fluxes with those produced by the line-by-line codes indicate that the model estimates are converging. Agreement is best in clear sky conditions; both clouds and aerosols introduce more disagreement. Comparison of model cloud with satellite cloud fields confirm that the models have difficulty in producing accurate cloud fields. It is believed that the models overestimate the incoming shortwave at the surface by 10-20 $W/m^2$ in the monthly mean and by twice that in daily averages. The accuracy of their estimation of longwave radiation at the surface is difficult to assess.

While radiation codes have been compared, models do not all use the same solar constants and astronomy. Difficulties in treating clouds stem from the mismatch between the thickness in levels in the models and the thickness of cloud layers, between the grid scales of the models and the size of the clouds such as oceanic stratus, the tendency of the models to predict 100% relative humidity too often, and uncertainties in the parameterization of the optical properties of clouds.

Improvement to the models would be aided by measurements of surface radiation at many discrete frequencies at the same time that concurrent vertical profiles of the atmosphere were collected. This type of measurement effort is being undertaken by ARM (Atmospheric Radiation Measurement program). ARM will include an island station in the western Pacific but will in general not make measurements in the variety of conditions experienced at sea. The ARM measurements are not practical at sea. However, broad band shortwave and longwave radiation measurements at sea can now be made to accuracies of approximately 1% and 5 W/m$^2$, respectively; and a number of ongoing observations made to these accuracies in diverse oceanic locations would provide a check on the accuracy of the model-produced radiation fields over the ocean. Similarly, the in situ observations would validate the accuracy of satellite estimates. Comparison of the accurate in situ data with the model and satellite estimates would identify errors in those estimates and indicate the need for further work if those methods are to provide data with the accuracy sought by the observing system.

## V.C.2. Measurement techniques for precipitation

The measurement of precipitation at sea remains one of the most challenging observational issues; a topic which is receiving considerable attention from the meteorological community (refer to Section IV.A). Wind flow over ships influences the collection efficiency of gauges, and the short space and time scales of precipitation make point measurements difficult to interpret. Thus, remote sensing techniques are attractive. Satellite based measurements, shipboard radar, and ocean acoustic noise monitoring show promise. In addition, the output of NWP models is displaying increasing skill in estimates of precipitation over land, suggesting that predictions over the oceans may be useful. We note that moisture divergence is the most direct source of information that can be obtained from model analyses to characterize the net surface fresh water flux. These approaches are briefly discussed below.

Satellite Techniques. There are several indicators of rainfall which can be derived from satellite observations. Based on the review by Arkin and Ardanuy (1989), we list the following methods:

*Highly Reflective Cloud (HRC)* – This technique uses visible light to identify those clouds which are most likely to be rain sources. The frequency of HRC can be related to rainfall measurements from atoll stations. It is somewhat subjective, suffers from poor diurnal sampling, and is restricted to the tropics. It does have the advantages of a long record, beginning in the early 1970s, and high spatial resolution. This is in part the focus of the WCRP Global Precipitation Climatology Project (WMO, 1991a).

*Outgoing Longwave Radiation (OLR)* – Values of OLR in the tropics respond strongly to variations in cloudiness, and is thus a useful index of convective activity. It has been used as both a qualitative and quantitative indicator of precipitation. Its sampling of the diurnal cycle, at twice per day, is better than HRC, though still suboptimum. It is restricted to regions where precipitation is primarily from deep cumulonimbus convection. OLR data are now being used to provide indirect estimates of the forcing by heating in NWP systems; these systems in turn are giving improved estimates of tropical precipitation (Puri, personal communication).

*Passive Microwave* – Two methods are available. Over the oceans the uniform background of microwave emission allows rainfall to be detected by the absorption of microwave energy (1.5 – 3 GHz) by raindrops. There are polar orbiting satellites carrying the appropriate sensors, so the technique shows promise for the important problem of high latitude, open ocean detection of rainfall. However, it cannot be used over land, snow or ice. The 30 km footprint is larger than most tropical rain cells, and the combination of partial occupation of the footprint and a nonlinear response to rain degrade its utility in the tropics. However, larger scale rain systems at higher latitudes may be adequately resolved by this technique. Because of spotty space and time coverage, accurate climate scale estimates of accumulation ($5^\circ$ x 1 month) may be problematic, though less so outside the tropics. In the tropics, the passive microwave satellites may be used to "calibrate" the OLR technique, which has better space/time sampling. The scattering of higher-frequency (~ 80 GHz) microwave energy by ice particles may also be used to detect rainfall. This technique offers better spatial resolution and can also be used over land surfaces.

*Tropical Rainfall Measuring Mission (TRMM)* – This rain radar satellite is to be launched in 1997 as a joint Japan/U.S. mission. It will fly in a low-altitude, low inclination orbit to provide good resolution at latitudes less than ±35° and will be non-sun-synchronous in order to sample the diurnal cycle over monthly periods. Rain radars must use additional information such as the reflectivity as a function of dropsize distribution, or direct rain gauge measurements, in order to estimate a rain rate. Comparisons with point measurements are good only to a factor of 2; however, averaging over large space and time scales improves the accuracy.

Surface Buoys and ships. The foregoing remote sensing techniques all require sea truth to generate credible precipitation products. This is a formidable challenge because the measurement of precipitation at sea is anything but routine. Indeed, successful rain gauge measurements from ships have yet to be obtained routinely. Various rain gauges types are in use.

- *Volumetric gauges* – manually recorded and emptied and automatically recorded/emptied sensors have been used on ships and buoys. Two examples of automatic gauges are those that fill, measuring the level capacitively, until a siphon is completed that quickly drains the gauge and those that count the drops that leave the catchment reservoir. With careful aerodynamic design, the best of these gauges are accurate to 10%. Such gauges have been deployed on research buoys and ships.
- *Optical rain gauges* – several rain sensors use the signal associated with rain drops interrupting a light beam. Difficulties in calibrating the instruments, possible effects of platform-induced vibrations, and assumptions about drop size distribution required to convert the output to a rain rate limit optical rain gauge accuracy to a range somewhere between 20-80% at present. These rain gauges are being tested on TOGA TAO moorings.

In the future, it is expected that optical or volumetric rain gauges on low-aspect Autonomous Temperature Line Acquisition System (ATLAS) buoys of the TAO array will constitute a valuable (and believable) source of reference data for validation of satellite precipitation retrievals. In the meantime, ordinary raingauges on small atoll islands provide the most useful readily-available validation data set over the Pacific. Mountain islands and warm atoll lagoons have a significant effect on the local precipitation regime but, this island bias can be minimized by choosing only the smaller coral islands.

Unfortunately, the sporadic nature of precipitation, particularly in tropical regions, limits the ultimate accuracy that can be achieved with rain gauges.

*Subsurface acoustic* – The ambient noise created by rainfall may be distinguished from that caused by wind by the peak near 15 kHz (Scrimger et al., 1987). This technique has the advantage of being an integral measure rather than a point sample. However, much work remains to be done (in particular, calibration against other approaches) before it can be considered a routine estimation method. The aim must be to deploy acoustic rain gauges on moored or drifting surface buoys.

*Ships radar* - Rainfall is estimated from meteorological radars operated from ships during special experiments (TOGA-COARE). While only good to 50 to 100% in individual comparisons, data on rain drop size distributions and averaging on larger space and time scales can improve accuracy to 10 to 25%.

<u>Numerical Weather Prediction Models.</u> The NWP models have been making improved estimates of rainfall in recent years, as confirmed at land stations. There is optimism that the surface fluxes of the hydrologic cycle will be more accurately modeled than the heat flux, because the constraint of water conservation and lack of complex radiation terms makes for a potentially simpler problem. Plans for a re-analysis of past weather data with a consistent model will provide a valuable climatological record for ocean surface fluxes. It should be possible thus to estimate the net fresh water flux (P-E) directly from the total atmospheric-column water flux divergence, integrated over the appropriate (large) spatial domain and over at least seasonal periods.

## V.C.3. Observing system requirements for surface heat and freshwater fluxes

The difficulty of defining accuracy requirements for surface variables has been discussed previously in relation to wind stress. For example, for use in atmospheric forecast models, the important criterion is the degree to which the data contain new information not already known to the model, and the impact of that new information on the model performance. The WOCE requirement for the surface heat fluxes is 10 W/m$^2$ for a mean value over a one month period and an area of say 2° latitude x 5° longitude (WCRP, 1984). For comparison, the expected changes in the annual mean surface fluxes due to increased greenhouse effect are expected to be of order a few W/m$^2$. For the water cycle, the mass flux equivalence of 10 W/m$^2$ in latent heat flux is 1 cm/month, a stringent accuracy requirement which can be met only over large areas using ocean flux divergence estimates. However, the buoyancy flux equivalent of 10 W/m$^2$ in net heat flux is about 5 cm/month, a goal which may be met by a combination of evaporation estimates based on VOS observations and satellite remote-sensed precipitation measures.

Accuracy requirements of order 1 to 10 W/m$^2$ for area-averaged surface flux can not be attained on a global basis by either in situ or satellite measurements alone; thus, it is necessary to consider alternative strategies. NWP models have (at least in theory) the ability to combine all data relating to the atmosphere using as constraints our knowledge of the operating physical processes. These data include atmospheric profiles from radiosondes and from satellites, as well as data describing the surface conditions. The models have the advantage of providing flux estimates uniformly on a global basis, although the accuracy of these estimates will vary geographically depending on the density and accuracy of the data available for initialization. The strategy for surface flux determination for the observing system is therefore expected to be:

(1) Use flux estimates from the analyses of atmospheric observations carried out by NWP models;
(2) Utilize surface observations as input to those models, and improve the coverage and accuracy of the data available for this purpose;
(3) Obtain flux estimates using in situ observations from ships and buoys, and compare these with model-generated flux fields;
(4) Calibrate the flux estimates using ocean budget techniques; and
(5) Encourage implementation of operational satellite missions capable of measuring flux-related surface parameters, especially satellite radiation estimates and surface wind velocities.

The fourth point requires some clarification. It is likely that, however carefully the flux estimates are made, there will remain a small systematic error which, while negligible for weather forecasting purposes, would become significant over climate time scales. Measurements in the ocean of the meridional heat flux across a particular latitude can be used to estimate the mean ocean to atmosphere heat flux for that ocean basin. Although such an estimate does not give the required spatial and temporal resolution, and does not partition the flux between the different components, it can provide an integral constraint on the detailed flux estimates. Thus, it will be still necessary to attempt to estimate the individual flux components and their spatial and temporal distribution using measurements and NWP models. The estimated fluxes will then be corrected for biases using an inverse estimation technique (see for example Isemer et al., 1989).

Continued development of the surface flux strategy will include tuning of the observation system to improve accuracy and cost effectiveness. It is expected that there will be an increased emphasis on data from satellites and from unmanned in situ vehicles whether moored, drifting, or capable of autonomous movement—as well as increased use of model-derived data. However, the collection of conventional in situ data must continue for system monitoring and evaluation and to ensure continuity of the climate database. In defining the satellite missions needed for ocean surface flux estimation, particular emphasis on determining the sea surface radiation budget is required. It is also important to determine the impact of the assimilation of data from new instruments, such as the ERS-1 scatterometer, on flux estimates provided by NWP models.

RECOMMENDATIONS FOR V.C

The recommended elements are essential for the measurement of surface fluxes and achieving subgoal 1c. This subgoal is required for subgoals 2a, 2b, and 3b. The existing elements are those systems presently able to provide global flux estimates either directly or through the assimilation of atmospheric and ocean surface observations in NWP models. The recommended immediate additions and future enhancements are either measurements for validation or for improved input to the flux estimation system, especially improved coverage in data sparse regions (e.g., the Southern Ocean).

Elements of existing observing systems:

C1. Flux estimates from analyses of atmospheric observations by NWP models.

C2. Marine data from VOS and drifting and moored buoys.

C3. Satellite based systems for estimating radiation and precipitation.

Elements to be added now to complete the initial observing system:

C4. Maintenance and, where possible, improvement of the present coverage and accuracy of VOS meteorological data. Coverage limitations are imposed by the number of merchant ships and the distribution of the shipping lanes. However, improving the accuracy of the observations, desirable in itself, can effectively increase the area for which an acceptable number of observations is available.

C5. Installation of gimbaled precision infrared radiometers (PIR) and precision spectral pyranometers (PSP) on selected VOS operating repeat tracks in diverse locations to provide the data needed for improving and validating radiation estimation schemes based on satellite data and models.

C6. Deployment of a small number of local buoy arrays measuring all the basic variables required to verify the flux estimates from NWP models (WCRP, 1989).

Enhancements to initial system:

C7. Definition and implementation of the operational satellite missions needed for ocean surface flux determinations (in addition to the polar orbiting and geostationary missions required for weather analysis and forecasting). Such missions are expected to have emphasis on determining the sea surface insolation, surface wind velocity, and precipitation.

Research and development:

C8. Implementation of long-term direct flux measurements at chosen in situ platforms should be considered. An example platform might be in the TOGA TAO array in the tropical Pacific Ocean.

C9. Research should be encouraged to develop, deploy, and evaluate at-sea precipitation sensors for use on ships, surface buoys, and moorings; these will provide in situ calibration data for satellite estimates of rainfall. The TOGA TAO array should be implemented with surface rain gauge sensors and a number of subsurface ambient noise detectors to test these devices while other in situ data are being collected.

C10. Evaluation of results from initial satellite missions to obtain large-scale estimates of precipitation, including polar and inclined orbit satellites carrying rain rate radars and to assess their efficacy as components of a precipitation observing system.

C11. Although it is assumed that the atmospheric community will recommend as part of the GCOS measurements of cloud condensation nuclei, it may prove necessary also to measure dimethyl sulfide in the ocean.

## V.D. Heat and Freshwater Transports and Budgets

### V.D.1. Measurement techniques

One approach to estimating heat and freshwater transports by the ocean is to integrate surface flux values. However, such estimates have limited accuracy and integrations cannot account for oceanic storage and release of heat and fresh water, so an independent measurement technique is required. Ocean-based estimates of the fluxes provide a valuable check on surface flux estimates and reveal the mechanisms and paths of ocean transports. Because changes in transport mechanisms provide important indicators of ocean climate response, we here discuss first the mechanisms and then the measurement techniques.

Mechanisms

*Thermohaline circulation.* At 24°N in the Atlantic, the overwhelming cause of the heat transport is the large scale thermohaline convection cell (Bryden, 1993). Northward flow of warm, surface waters and southward flow of cold, deep waters effects a significant heat transport (1.2 PW). Since the flows are basin scale, it appears necessary to measure a complete T, S transect to estimate heat transport. Monitoring deep western boundary currents is not sufficient, because strong recirculations are part of the boundary current regime in many areas (Schmitz and McCartney, 1993), changing property values without adding to the net fluxes.

*Ekman transport.* This too is a meridional overturning cell, but a rather shallow one. Water transported within the Ekman layer is warmer than the deep compensating flows. While small at 24°N in the Atlantic, it carries half the heat flux in the much wider Pacific at the same latitude. It is generally estimated from: 1) upper ocean temperature and velocity observations (via acoustic Doppler current profiler (ADCP) or Lowered ADCP) differenced with the underlying geostrophic flow or 2) from estimates of the wind stress. In method 2, assumptions about the depth of the Ekman layer must be combined with temperature and salinity profiles in order to estimate fluxes.

*Horizontal circulations.* The basic horizontal ocean gyres are driven by the curl of the wind stress in the interior and closed by a boundary current at the western coast. These transport heat if there are temperature differences between interior and boundary flows, such as can arise from the spatial distribution of air-sea heat exchange. In the subtropical North Atlantic, the temperature differences are such that a very small equatorward heat transport is effected. However, in the subtropical North Pacific, the horizontal cell accomplishes half the poleward heat flux. Full transoceanic sections are necessary to calculate the heat and freshwater fluxes due to the horizontal gyres, as well as to define the extent and strength of the gyres. Where practical, it is valuable to monitor the western boundary currents (as done with cables across the Florida Strait).

*Eddy fluxes.* The spatially and temporally varying velocity, temperature and salinity fields of mesoscale eddies can transport heat and salt, given a correlation between the different fields. (In the atmosphere "eddies" are an important mechanism for meridional heat transport.) Eddy fluxes play different roles in different parts of the ocean; negligible in the subtropical North Atlantic, dominant in the Antarctic circumpolar current. The presence of eddies dictates higher spatial resolution sampling for surveys (i.e., scales to the Rossby radius must be resolved). Failure to do so could potentially lead to aliased estimates of the fluxes, if the eddies are strong enough and sufficiently variable. An example of this may be found in the tropical North Atlantic, where large seasonally variable standing eddies are found, in an area with strong temperature and salinity contrasts (Richardson et al., 1994). Moored current meters and temperature recorders are the primary means by which eddy heat fluxes have been estimated in the past (Bryden and Brady, 1989). A satellite altimeter can provide statistics on the presence of eddies, but information on the vertical distribution of temperature and salinity is necessary for flux estimates. This may be obtained from repeat hydrographic sections done with sufficient frequency and resolution, say with XBTs on VOS (see also Section IV.B and Figure IV.B-4).

*Marginal sea exchanges.* Many oceanic regions have important exchange sites with marginal seas (usually narrow straits) (Tomczak and Godfrey, 1994). Good examples are Fram Strait, connecting the Arctic with North Atlantic deep-convection sites, and the Straits of Gibraltar, through which Mediterranean Sea water strongly influences the salinity structure of the entire North Atlantic Basin. For freshwater budgets, river discharges must be known. These are generally available, but often the monitoring sites are hundreds of kilometers upstream of the mouth. In remote areas (e.g., Siberia), many small rivers are not gauged, yielding a aggregate uncertainty which may be substantial.

Measurement Techniques

*Meridional heat and freshwater transports.* Our primary means of measuring ocean heat, salt, and freshwater transports is the use of transoceanic hydrographic sections. In addition to providing constraints on surface fluxes, hydrographic sections provide insight into the mechanisms of ocean heat and freshwater fluxes and checks on the trends in deep water properties, depending on the frequency of repetition. Transocean sections must be complemented with marginal sea exchange measurements and accurate river flow measurements in order to develop complete budgets.

The "direct" method of flux calculation appears to yield an accurate estimate of mean meridional heat flux, which, in the Atlantic, is largely carried by the baroclinic overturning cell. Estimates of heat flux at 24°N from section data taken 23 years apart are indistinguishable and are estimated to have an error of no more than 10% (Hall and Bryden, 1982; Roemmich and Wunsch, 1985). Recent model runs (Böning and Herrmann, 1994) indicate that the North Atlantic response to wind stress variations is mainly barotropic, and thus does not substantially change the density field. While other oceans may be more sensitive to seasonal variability, these results suggest that further repetition of zonal hydrographic sections would be an important contribution toward understanding the global water and heat cycles.

The latitudes of most interest for the global water cycle are distinct from those that best define the meridional heat flux. Ocean water fluxes reach extrema at around 10° and 40° N and S, reflecting evaporation in mid-latitudes and precipitation at high and low latitudes. In contrast, heat flux is maximal at 25°-30° N and S. If the freshwater flux divergence could be estimated to about 0.1 x $10^6 m^3/s$ (of order 10% of the flux) from hydrographic data at 40°N and 10°N in the Atlantic, this would correspond to an error in E-P of about 12 cm/yr, significantly less than the differences between present climatologies. With few zonal ocean sections having been occupied, and none on a seasonal basis, it is difficult to estimate the error of such calculations due to unsampled seasonal and interannual variability, but it is likely to be of order 0.1 x $10^6 m^3/s$. The WOCE Hydrographic Programme (Core Project 1) will improve the global coverage of sections, however, long time series of repeat sections would be a very valuable follow-on to the first-order picture developed from the WOCE data set. Occupation of sections with seasonal resolution may be justified at some latitudes (10°N), while others with a weak seasonal cycle (24°N) might be occupied every few years. In the Atlantic a zonal section can be completed in less than three weeks. As a example, we note the 27 occupations of a section at 165°E, from 20°S to 10°N, over a seven-year period by France, U.S.A., and PRC during TOGA. Considering the large number of countries with strong oceanographic programs around the Atlantic, it should be relatively easy to focus resources on repeat occupations of several zonal sections in that ocean.

*Strait monitoring.* Bering Strait is the main mass flux conduit for water returning from the Pacific to the Atlantic, and an important source of buoyancy for the Arctic Ocean. K. Aagaard (U. Washington) has a partial monitoring program underway to record the transport through the Strait. Coachman and Aagaard (1988) estimate a standard deviation in interannual variability in Bering Strait transport of about 0.1 x $10^6 m^3/s$. This seems large enough to have climatic significance, especially for the Arctic ice budget. A more complete monitoring program, including salinity measurements, would be a very valuable climate indicator for the high latitude fresh water budget.

The two layer flow at Gibraltar is the result of a loss of water to evaporation in the Mediterranean basin that represents one of the larger terms in the North Atlantic salt budget. Fram Strait carries freshwater and ice from the Arctic to key deep convection areas of the North Atlantic. It is clear that time series measurements of transports in these straits would be very valuable in deciphering oceanic climate response to variations in freshwater forcing. If maintained in the long term, such programs would provide strong constraints on basin scale surface water fluxes. For the Mediterranean, the constraint on the water budget provides a link with the heat budget through the latent heat term (Garrett et al., 1993). Improved Gibraltar flux measurements could be instrumental in deciphering the ongoing controversy about exchange coefficients and radiation terms in the surface heat fluxes.

Global constraints on ocean transports and budgets would be provided by measuring interocean exchanges of heat and salt by the ACC. This does not yet seem feasible except as a special research program. However, new approaches are under consideration.

*Heat and salt budgets.* Any flux divergence calculation depends on an assumption (or direct measurements) of the time dependence of the properties within the control volume. Usually it is assumed that the volume is in steady state, an assumption which introduces some undetermined error (e.g., Bradley et al., 1993). Thus, monitoring of water column heat and salt content is a valuable complement to ocean flux estimates. The time scale of the required sampling is a function of the depth; biweekly temperature and salinity profiles, e.g., obtained by an array of profiling Autonomous Lagrangian Circulation Explorer (ALACE) floats, would suffice to resolve the seasonal cycle in the upper ocean, whereas a hydrographic section every five years may be sufficient to resolve climatic trends in deep temperatures. The XBT (and XCTD) as deployed from the VOS, are an important means of monitoring upper ocean heat (and salt) content (See Section V.E). In addition to profiling ALACEs, moored CTD profilers are under development for monitoring full ocean depth heat and salt content. Pairs of such instruments could be used to continuously measure the geostrophic transport between them, so long as the intervening bathymetry is not overly complex.

V.D.2. Observing system requirements for heat and freshwater transports

RECOMMENDATIONS FOR V.D

Elements of existing observing systems:
D1. Monitoring of river discharges.

Elements to be added now to complete the initial observing system: None.

Enhancements to initial system:
D2. Periodic occupations of hydrographic sections at ± 24° to 30° in each ocean basin for estimation of heat flux. The recommended repeat period might be five years at 24°N in the Atlantic to monitor the strength of the thermohaline circulation and understand climatic

trends in the deep waters; a repeat time of 10 years in the other basins may be sufficient for monitoring purposes, though new information could necessitate more frequent occupations.

D3. Periodic occupations of zonal hydrographic sections at approximately ± 10° and 45° in each ocean basin for estimation of freshwater flux. Repeat time should be 10 years, although "burst" sampling, or continuous monitoring of key components, should be considered to resolve the seasonal cycle.

D4. Monitoring of the exchanges at key straits. Bering, Fram, and Gibraltar are choke points where major components of the freshwater budget can be readily measured.

D5. Deployment of temperature and conductivity measuring autonomous profilers (e.g., ALACE floats).

Research and development:

D6. Research is necessary to establish accuracy and variability of meridional transports recommended as 2 and 3 above.

D7. Encourage research to develop and evaluate autonomous techniques for temperature and conductivity measurements (e.g., CTD profilers).

## V.E. Upper Layer Temperature, Salinity, and Velocity

This section provides a discussion of the observing system observations required in the upper ocean. The scales of variability of the upper ocean have been described in Section IV.A-D. Some upper ocean measurements are discussed elsewhere in Section V. In particular, sea level, which on seasonal scales provides estimates of upper ocean thermal storage as well as dynamic height, is discussed in Section V.F. Altimeter sea level measurements combined with in situ thermal data may well provide the key information for the next generation of coupled ocean-atmosphere prediction experiments.

The historical data base. The historical upper ocean data base has been exploited for many purposes, including global ocean temperature climatologies such as those of Levitus (1982). Meyers and Donguy (1984) and Harrison et al. (1989), among others, have studied heat storage in the mixed layer using data from the broad-scale sampling programs. Kessler and Taft (1987) and Picaut and Tournier (1991) used upper ocean data, combined with surface salinity measurements and an estimate of the mean T-S relationship, to study the dynamic height and zonal geostrophic transport in the central tropical Pacific during 1979-1984.

The existence of relatively long, well-sampled XBT lines in the Pacific Ocean has enabled the estimation of the relevant temporal and spatial scales of variability (White and Bernstein, 1979; White et al., 1982; Meyers et al., 1991), which in turn have formed the basis for quasi-operational analysis and assimilation schemes (Ji et al., 1994a; Smith et al., 1991).

### V.E.1. Methods for measuring upper layer temperature, salinity, and velocity

The discussion of methods is arranged broadly by platform, though this choice is somewhat arbitrary because the same platform is often used for several purposes. It is important to assess such multi-purpose facilities, keeping the broader objectives of the GOOS and other non-climate operational systems in mind.

In the upper ocean, temperature measurements are routinely obtained from the VOS XBT program and salinity seems to be obtainable from VOS through the use of XCTDs. Both temperature and salinity can be obtained using instruments on moored arrays such as TAO. Acoustic thermometry offers some potential for monitoring long-term climate thermal change, though principally beneath the upper layers. Subsurface floats are a new and promising technology being used to obtain temperature profiles through the thermocline (conductivity measurements are being tested).

For velocity, moored arrays are the main method, although ADCPs mounted on research and merchant vessels are increasingly being used for routine monitoring of current structure and strength. They provide direct velocity measurements for the upper 200 to 400 m of the ocean. Drifting buoys and ship drift estimates provide Lagrangian estimates of the velocity of the surface layer while subsurface floats provide a similar capacity below the surface.

Indirect methods, such as feature analysis of subsurface structure based on remote sensing of SST and obtaining geostrophic currents from estimates of the dynamic height using sea level and density data are alternative sources of information for both the velocity and mass fields.

XBT and XCTD Sampling. The XBT remains a relatively inexpensive, easy to deploy instrument for sampling upper ocean temperature. It has been in use for over 25 years and has been deployed from merchant vessels for the past 15 years. The major proportion of XBT deployments in recent times have emanated from the VOS program which has, for the most part, been funded through research programs or maintained through navy and fishing fleet cooperation. Measurements can be taken while the ship is underway, with minimal operator action, and communicated in near-real-time usually in the form of inflection point data. Technical details of the XBT program can be found in Sy (1991). In many cases the generation and transmission of temperature (BATHY) messages from VOS is done automatically.

Figure V.E.1-1 shows the distribution of subsurface data for 1990 (principally from XBTs) and, for comparison, the distribution of data in a single month based on real-time and delayed-mode collection and based on real-time collection alone. It shows the limitations in the geographic coverage of merchant shipping as well the frequency and dependability of certain lines. While adequate monitoring and analysis is possible with the real-time data set, higher quality products and more effective quality control are available using the greater quantity of data available in delayed mode.

While some XBT technical problems have been identified and corrected, such as deficiencies in the fall-rate equation (Hanawa et al., 1994), the instrument and the method of volunteer deployment have proven effective and reliable. Perhaps the greatest virtue of the XBT has been that its simplicity has assured a high level of experimental repeatability (different, non-technical operators usually obtain the same result). Recent developments with automated launch systems may allow more precise prescription and control of deployment in the future. Probes designed to go to 750 m are most commonly used, but technical problems can lead to loss of information towards the end of the fall. For some years an XCTD has been under development to provide simultaneous measurements of temperature and salinity versus depth. It offers the potential of sampling the upper ocean baroclinic structure rather than just the thermal contribution. Although its operational use is promising, it is probably premature to rigidly specify observing system sampling methods.

The TOGA and WOCE upper ocean sampling strategy was discussed in Section IV.B. The broad-scale XBT sampling strategy for the tropical oceans calls for one XBT drop per 1.5° latitude and 7.5° longitude, with cruise tracks repeated 12 times per year. This sampling rate would yield monthly-averaged subsurface temperature analyses accurate to around 0.5-0.7°C or 10 m in isotherm depth over the tropical regions, and around 0.3°C in temperature or 4 m in isotherm depth in regions of heavy shipping traffic (Meyers and Phillips, 1992; TWXXPPC, 1993). The frequently repeated trans-equatorial sections aim for a profile at each degree of latitude 18 times per year improving the accuracy to around 6 m in isotherm depth and providing better resolution of the important equatorial ocean current system. Using only XBT observations, useful accuracy (say, 0.5°C) would be achieved in less than one half of the tropical ocean regime. However, combined XBT and mooring networks (discussed later) together are meeting TOGA requirements in the equatorial region but are only marginally adequate for the tropical Pacific in general (cf. TWXXPPC, 1993).

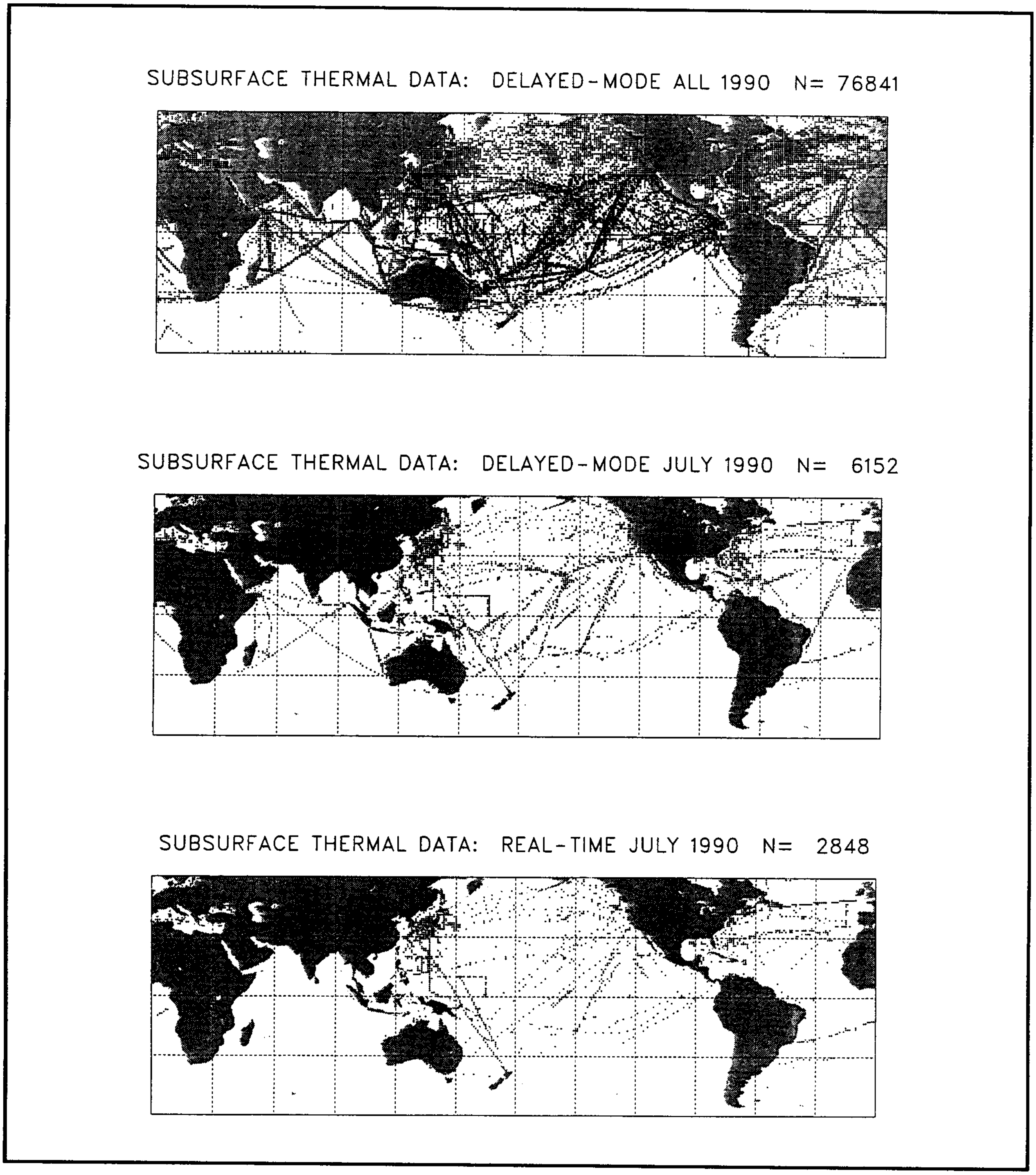



Figure V.E.1-1. Distribution of upper ocean thermal data. (upper) Annual total upper ocean thermal data for 1990 as represented in the U.S. National Oceanographic Data Centre archives at the beginning of 1993 (courtesy of M. Hamilton as part of the WOCE Data Assembly Centre scientific quality control project). (middle) Distribution of upper ocean thermal data for July 1990 from the same data base as (upper). (lower) Real-time data collected in July 1993 from the Melbourne, Australia node of the GTS, as an example of real-time data distribution.

In addition to the equatorial Pacific, in support of TOGA goals, XBT use is concentrated in the North Pacific (the TRANSPAC program) and North Atlantic Oceans. There are large areas which remain severely undersampled, mainly in the Southern Hemisphere though recent initiatives using Antarctic supply vessels have partly redressed this imbalance. Broadcast mode sampling, as practiced in the North Pacific TRANSPAC region, is clearly useful for monitoring low-frequency, large-scale storage and transport of heat (see TWXXPPC, 1993 and the discussions in Sections IV.B and IV.E) and is providing a useful data base for monitoring seasonal to decadal scale variability, although it still does not meet WOCE requirements (White, 1993). The Atlantic Ocean network provides adequate data for large-scale monitoring and descriptive studies but at present is not adequate for producing temperature estimates to the standards set by WOCE (Festa and Molinari, 1992). The Indian Ocean network is adequate for understanding seasonal variability in some regions but is limited by the length of record for studies of interannual variability or by coverage for mapping the entire Indian ocean thermal structure (Godfrey et al., 1995). Outside of these regions the present network is generally inadequate.

Outside the tropical oceans, mesoscale eddies and fronts are the dominant characteristic of ocean variability and the spatial sampling requirement is correspondingly more severe. Even if eddies do not need to be explicitly resolved, the sampling method must take into account this variability to avoid aliasing. The WOCE high-density lines aim for 50 km resolution (finer in the vicinity of fronts and boundary currents), but use reduced temporal sampling (around four times per year). The sufficiency of this sampling rate for resolving the transports of heat and mass by geostrophic currents at approximately seasonal time scales is being evaluated (Roemmich and Cornuelle, 1993).

For some regions commercial and naval traffic is such that mesoscale, relatively high-frequency temperature variability can be monitored and, in some cases (e.g., the Gulf Stream and Kuroshio current) the data can be used for initializing short-range (order weeks to months) ocean models. In some cases aircraft-deployed XBTs are often utilized. Robinson et al. (1989a, b) and Clancy (1992) provide examples of such applications for the Gulf Stream. The Monthly Ocean Report of the JMA regularly utilizes such data in their analyses of the Kuroshio Current path and variability in its vicinity.

Moored Technology. Moored time series measurements of the upper ocean are attractive because of the possibility of equipping moorings with many different kinds of complementary sensors thus providing additional information at minimal extra cost. Moored technology can be used for both temperature and velocity profile measurements. Conductivity also can be measured to estimate salinity (McPhaden et al., 1990; Sprintall and McPhaden, 1994), at some cost relative to temperature in terms of servicing and calibration, but will not be discussed in detail here. Using moorings a properly designed temporal sampling scheme can define the frequency spectrum of variability with minimal error introduced by aliased short period fluctuations.

The TAO array as it is now constituted includes an ATLAS array with elements spaced approximately every 15° of longitude along the equator and at latitudes of 0°, 2°, 5° and 8° north and south (Figure V.E.1-2). TAO typically provides samples every 20 m down to about 140 m and then several more widely spaced samples down to 500 m (usually around 11 levels in all). In addition, surface air temperature, relative humidity, and surface wind are often provided (Sections V.A, B, and C). Several hourly samples per day plus daily averages from each sensor are relayed in real-time through Argos. Interspersed among the ATLAS moorings at 20-30° separations along the equator are a small number of Profile Telemetry of Upper Ocean Currents (PROTEUS) and conventional current meter moorings to measure the upper ocean circulation. PROTEUS measures and telemeters current profiles in the upper 250 m from an ADCP mounted in a surface buoy. PROTEUS moorings also measure surface winds, SST, air temperature, relative humidity and subsurface temperatures, transmitting all but the latter in real-time. A subset of TAO ATLAS and PROTEUS moorings measure salinity, rain rate and incoming solar radiation. The TAO array was planned to consist of nearly 70 moorings by the end of 1994 (McPhaden, 1993; Figure V.E.1-2). The array is maintained by a multi-national base of support, which at present involves a cooperation between the United States, France, Japan, Korea and Taiwan. Other moorings have been routinely maintained in the Northwest Pacific by Japan (presently three) and on a trial basis at 80°E on the equator in the Indian Ocean.

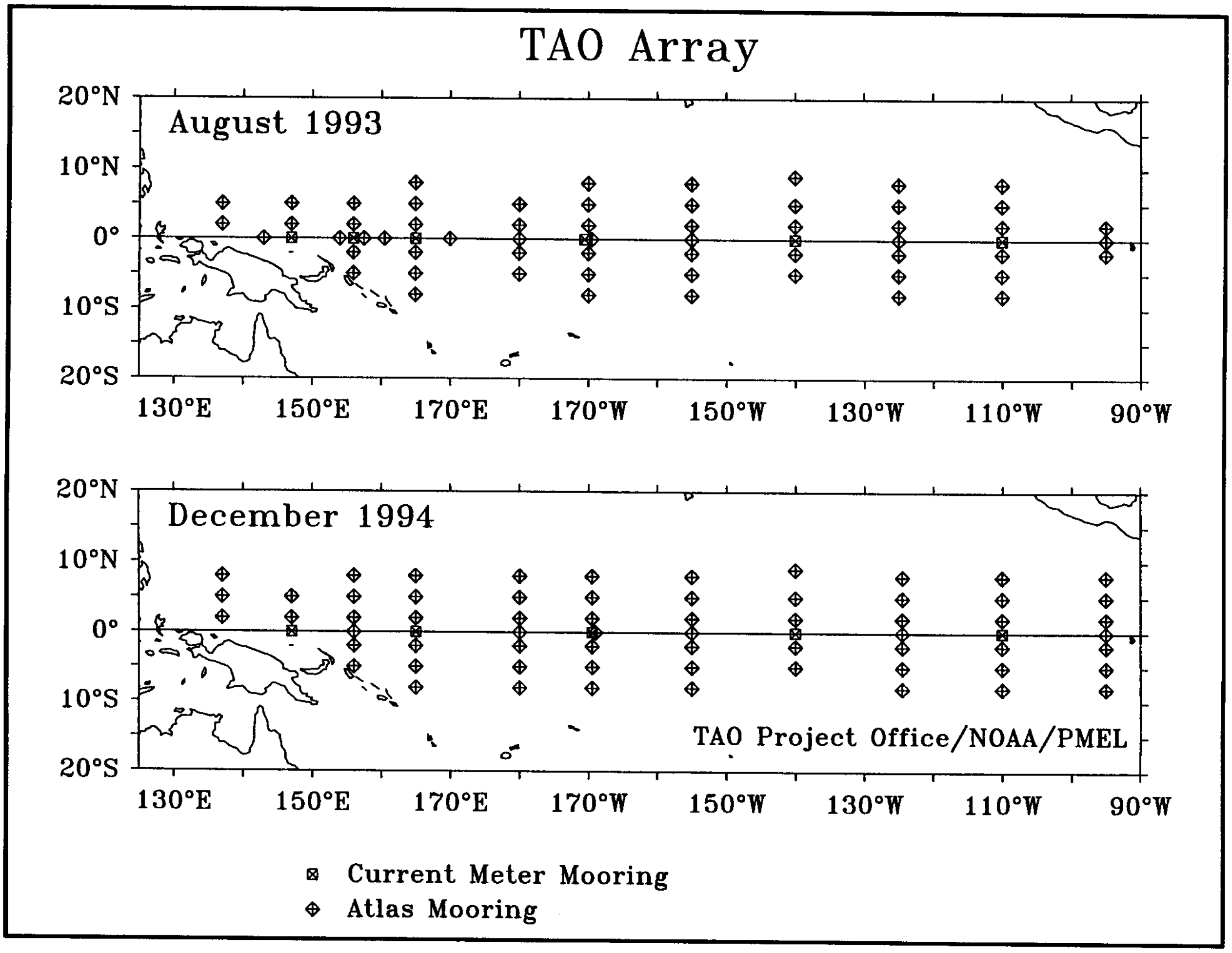



Figure V.E.1-2. The TOGA Tropical Ocean Atmosphere array in the Pacific Ocean (from McPhaden, 1993) as it existed in August 1993 and its planned final configuration December 1994. ATLAS moorings, denoted by the diamonds, will be deployed at the nominal locations of 8°N, 5°N, 2°N, 0°, 2°S, 5°S, and 8°S approximately every 15° of longitude from 95°W to 137°E (the southern portion of the array is blocked by islands in the western Pacific). Embedded in this array are equatorial current moorings at the five locations indicated by the squares. The mooring site on the equator at 110°W has been occupied continuously since 1980.

The strength of the TAO array for short-term climate studies derives from the suite of high accuracy, real-time measurements. The spatial sampling of the TAO mooring derives principally from consideration of the surface wind stress (Hayes et al., 1991). However, it is also adequate for resolving the main patterns of tropical upper ocean variability; the high temporal sampling rates are able to resolve energetic high-frequency fluctuations which are not resolved by weekly to monthly VOS sampling (McPhaden, 1993).

Data from the TAO array are distributed by Pacific Marine Environmental Laboratory (PMEL) to the research and operational community in both real-time and delayed mode by various means (internet, dial-up phone line data base, floppy disk, etc.). Delayed mode TAO data are also available from the U.S. National Oceanic Data Center (NODC), NCDC, and the subsurface data center in Brest, France. A subset of the TAO Argos data stream is retransmitted on the GTS. Subsurface thermal data from the TAO array are assimilated directly into ocean models and analysis systems (see Figure I.B.1-2 for an example). New telemetry systems, capable of higher data rates than Argos and providing two-way capability, are being tested for use on TAO.

The longest deep ocean moored time series derives from a surface mooring site maintained by NOAA/PMEL at 0°, 110°W in the equatorial Pacific as part of the Equatorial Pacific Ocean Climate Studies (EPOCS) program. This site was first occupied in January 1979 and, after a record break of several months, has been maintained continuously since March 1980 to the present. A second EPOCS/TOGA mooring site maintained by NOAA/PMEL at 0°, 140°W since April 1983 is over 11 years long. These equatorial moorings served as the nucleus for the more ambitious basin scale TAO array.

Looking to the future, technological developments are underway to simplify mooring design, enhance capabilities, and/or reduce costs. Examples are Oregon State University's development of an expendable subsurface current meter/temperature mooring; WHOI's ongoing effort to evaluate moored sensors for air-sea interaction studies and develop extended-life surface moorings for all environments, including severe conditions such as those in the subpolar regions and in the Arabian Sea; and PMEL's efforts to design a next-generation ATLAS mooring system. Once perfected, technological developments like these could be available in the observing system for more cost-effective measurements.

Indirect methods. SST has long been used to identify significant ocean variability, although the connection between surface signatures and subsurface structure is not straightforward. One promising avenue is to use SST data to identify the horizontal structure and principal horizontal circulation features (so-called feature analysis) and project this information onto the recorded (climatological or otherwise estimated) temperature profiles typically associated with such features. Clancy (1992) discussed some routine applications of this technique. An alternative and possibly more promising method is remote sensing of sea surface height using altimeters (see Section V.F). Such measurements provide an estimate of upper ocean dynamic change, albeit indirectly through its manifestation as an associated change in sea surface height. Altimeters provide both global coverage and horizontal resolution not possible with other methods. Recent comparisons of dynamic height anomalies estimated from TAO and from TOPEX/POSEIDON suggest the agreement is within 2 cm (Picaut, personal communication).

At present we cannot quantify the contribution of remotely sensed data in sampling the upper ocean. For the tropical oceans, it is clear the information provided in wind stress and SST analyses overlaps (is not independent of) that provided in upper ocean temperature samples, but the degree of redundancy remains uncertain. Outside the tropics, the overlap may be less because more of the signal is due to internal variability.

Drifters (ships and buoys). Estimates of mean and eddy kinetic energy of surface currents based on ship drift information have been compiled on several occasions. However, such estimates do not cover the entire ocean, are biased in accuracy because of preferences for particular shipping routes, and sample a usually unknown portion of the near-surface current depending upon the ship draft. Ship drift data contain both geostrophic and Ekman surface flow components. Some ship drift data are available in real-time as TRACKOB messages on the GTS.

Drifting buoys have been used since the 1970s to provide mean sea level pressure data in regions not covered by the VOS program. The buoy drift could be used to follow surface currents but, due to the uncertain current following characteristics of these early buoys, drift velocities were difficult to analyze. More accurate data on near-surface velocity are being obtained from the surface drifters deployed in both TOGA and WOCE. It is feasible to reduce the current-following error (due to wind forcing) to 2 cm/s in 10 m/s winds (WCRP, 1988b). It is planned to achieve global coverage of at least one drifter in each ocean area not larger than 600 km$^2$ for a five-year period. This will be adequate to make statistical estimates in each square representative of the observing period. WCRP (1988a) indicates this sampling would give an estimate of the mean velocity good to 10% of the eddy variability. Much of the seasonally and perennially ice-covered regions of the ocean will not be sampled. Such drifters also collect SST and, in some cases, mean sea level pressure and so may be justified independently of their ocean current-following information. The data are regularly transmitted, along with the buoy position, through Argos and, in most cases, are available in near-real-time.

Floats. Subsurface floats, for example ALACE, are capable of cost-effectively measuring profiles of temperature, and potentially salinity, on the way to the surface where the information can be transmitted via Argos. Thus, this technology can provide information on upper ocean temperature and salinity, although the strategy of deployment using ships of opportunity to meet the requirement of reasonably uniform coverage in the presence of float convergence and divergence remains to be developed. For more information on ALACE see Section VII.B.2.

Other autonomous vehicles are being developed but none are a practical option for measuring upper ocean temperature, salinity, or velocity at this stage.

Acoustic Doppler current profilers (ADCPs). Acoustic Doppler current profiling can provide (relative) velocity in approximately the upper 400 m of the water column routinely from ships. The Japanese regularly take ADCP measurements from a number of merchant and fishing vessels operating near their islands. For several years they have reported data from 70 to 100 ship-mounted ADCPs. Figure I.B.1-1 provides an example of a surface current chart based on ADCP data as well as ship and buoy drift data. Some research programs obtain ADCP data now from research vessels and from VOS. The TOGA and WOCE research programs are obtaining ADCP data during hydrographic surveys on research ships and along a few selected VOS lines in the Pacific Ocean. ADCPs are also used on some fixed moorings (see previous discussion of TAO), though in regions of high bioproductivity they may be subject to error induced by free swimming scatterers (i.e., fish; see Pullen et al., 1995).

It seems unlikely that global current measurements will be obtained from ADCPs, though it is conceivable that a significant portion of the VOS could be equipped with them. ADCP measurements are presently expensive and may not be justifiable given their present return. However, they should not be ruled out because there are ongoing developments and the cost has been substantially reduced in recent times. One ADCP development is toward instruments which should return velocity profiles through much or all of the water column, using lower frequencies and larger vertical averaging bins. Another is toward multiple positioning systems and better compasses which may yield profiles of true (rather than relative) velocity with acceptable error bars. These developments could lead to the inclusion of ADCP measurements as part of the regular observing system hydrographic sampling work, in order to obtain estimates of the vertical profile of the kinetic energy of the major ocean gyres.

Acoustic thermometry. This method offers an alternative way of sampling ocean temperature, though principally through the deeper ocean below the thermocline (see Section VII.B.2 for further discussion). It is not a realistic option for the goals being addressed here.

## V.E.2. Observing system requirements for upper layer temperature, salinity, and velocity

The following discussion introduces and provides justification for a series of recommendations to satisfy the upper ocean subgoals introduced in Section III.B.

The observational elements required to meet a particular subgoal will require ancillary data and products from other subgoals, particularly those concerned with surface fluxes of heat and momentum and the determination of SST (see previous Sections V.A-C and VIII). That is, upper ocean data are more valuable in the context of the entire observing system than they are when used in isolation. In turn, upper ocean data will be used directly in meeting other goals such as monitoring and understanding deep, low-frequency ocean variability and the construction of climatologies (goals 3 and 4) and may be indirectly used in verifying and inferring surface fluxes. It would seem likely that the upper ocean sampling requirements for goal 2 will adequately cover those of the other goals.

Subgoal 2a. "To provide global data for monitoring, understanding and analyzing monthly to interannual upper ocean temperature and salinity variations."

The principal concerns are the analysis of large-scale storage of heat at interannual and longer time scales over the global ocean; the strength of the subtropical gyres and major boundary currents, usually indirectly inferred from changes in temperature or perhaps sea level/dynamic height; changes in sub-polar circulation and stability (e.g., the propensity for deep mixing); and the description of the seasonal cycle of currents, temperature and salinity on large spatial scales. Prediction is not a focus for this subgoal. The seasonal cycle of temperature, salinity and currents, and their variance, is poorly known over much of the global ocean. Their determination requires a relentless, systematic collection of data with global coverage but modest resolution. Such data sets provide fundamental baselines for research and development of the ocean observing system for climate.

It is critical that present routine global sampling programs be maintained. The TRANSPAC data have yielded significant scientific benefits and if maintained would, in terms of the present charge to monitor, understand and describe climate change, deliver considerable benefits to the observing system. The TRANSPAC survey region provides one of the few places where the data are sufficiently dense and the record of sufficient duration to follow changes in heat storage and changes in subtropical gyre strength. The record remains short when set against the requirements of the observing system but it is nevertheless a significant base on which to build. The North Atlantic Ocean provides another region where such monitoring appears feasible though, as with the North Pacific, there is no hard scientific evidence on minimum requirements for such monitoring. Elsewhere there appears to be a sound case for long-term enhancement of the VOS scheme though, in practice, the options are limited.

There is already substantial regional sampling, principally through fishing and naval fleets, towards this subgoal though of course it is restricted. It is important that the ocean observing system for climate recognize and encourage such regional, high-density sampling systems even if they are not totally within the guidelines of ocean climate as adopted here. They provide invaluable sampling of variability, though in restricted domains, as well as providing substantive products for the user community, an aspect in which the climate observing system is relatively immature. The intention in many cases is to combine the in situ data with altimeter measurements, as available, in order to initiate short range (week to month) ocean prediction.

Subgoal 2b. "To provide upper ocean data in the tropical Pacific Ocean for the initialization and verification of models for ENSO prediction."

This subgoal is directed at providing data for monitoring and predicting ENSO via three-dimensional upper ocean analysis and data assimilation into ocean and coupled ocean-atmosphere models and at providing data useful for validating and improving such predictions.

In order to achieve subgoal 2b (successful ENSO prediction) it is recommended that the existing Pacific equatorial VOS XBT and TAO systems be maintained, effectively at their present levels. At this point it would appear to be unwise, even foolhardy, to suggest any substantial reduction of the present sampling strategy. Recent research indicates the present system is delivering real benefit, both in terms of scientific product and in terms of quasi-operational products (TWXXPPC, 1993). In the tropical Indian Ocean and Atlantic Ocean, there would appear to be some case for enhanced sampling though the scientific case for such enhancement (as part of the observing system) is not yet overwhelming (see also subgoal 2c discussion).

There is some uncertainty in regard to the information needed for model initialization and for detecting tradeoffs between thermal sampling designs. While a great deal has been learned from the TOGA program and experimental ENSO prediction, it is not yet clear how critical subsurface temperature data are to the skill of model prediction. The discussion in TWXXPPC (1993) and recent research results (e.g., Ji et al., 1994a) are suggestive but not conclusive, principally due to the shortness of the record. Successful predictions have been made on the basis of past SST or wind patterns (or a combination of both) so at least part of the necessary information is available irrespective of upper ocean data. However, present knowledge of ENSO emphasizes heat storage and upper ocean "memory" and there have been preliminary demonstrations that such data will play an important role (Ji et al., 1994b). NRC (1994) reaches a similar qualitative conclusion in respect of upper ocean data in support of research and "operational" short-term climate prediction.

The question of observing system redundancy has also been a topic of some debate (TWXXPPC, 1993; NRC, 1994). At this point the evidence would appear to support the contention that, together, the TAO and VOS XBT elements form a powerful observing system, perhaps over-designed but not obviously so (TWXXPPC, 1993). Improved understanding of the mechanisms of interannual variability and of the sensitivity of analysis and prediction systems to different types of data is required before firm recommendations can be made. Observing system experiments should be used to identify the essential input of individual elements of the upper ocean temperature sampling network, as well as possible redundancy within this system and with wind, SST, and sea level observations.

Upper ocean currents are recognized as a valuable means for validating ocean analysis and coupled ocean-atmosphere prediction schemes (e.g., Hayes et al., 1989) but their worth in terms of model initialization is more problematical (Anderson and Moore, 1989). The major sources of such data at present are the PROTEUS moorings and conventional current meters within TAO and the tropical ocean surface drifter array. The moorings provide multi-purpose platforms and thus current meters would seem to warrant support within the observing system because of the minimal additional cost. The drifter network has provided significant surface current data and, with their additional use as SST platforms, would appear to be justified as a significant element of the design.

The paucity of knowledge on the importance of subsurface salinity suggests such measurements should not be given high priority at this time, but scientific developments should be kept under review (e.g., TOGA-COARE). However, again keeping in mind the desirability of contributing to the baseline of data, it is sensible to take measurements wherever this adds little to the cost of the sampling program. Therefore, VOS and TAO salinity measurements should be encouraged.

Subgoal 2c. "To provide upper ocean data outside the tropical Pacific for the understanding and description of ocean variability and for the initialization and development of present and future models aimed at climate prediction on seasonal to interannual time scales."

### V.E.2. Observing system requirements for upper layer temperature, salinity, and velocity

The focus is on the general problem of climate prediction, other than ENSO, at scales commensurate with the major upper ocean variability. It includes data for mixed layer models, for delineating important oceanic features, as well as data for assimilation/analysis by ocean models. At this point in time it is unreasonable to contemplate global upper ocean observation, although the surface fields of SST, wind, and sea level are relevant and possible to obtain. The design is at an early stage according to the sequence set out in Section III.D but in some regions there is sufficient experience, knowledge, technology and reason (i.e., a clearly definable purpose and outcome) to recommend and maintain an in situ observing system. The regional monitoring of the Kuroshio, mentioned in Section I.B.1, is an example, though strictly some of the activity falls outside the domain of climate and into other modules of GOOS.

At this time there is a well researched connection between upper ocean data and prediction for the tropical Pacific and ENSO. The observing system must build in some visionary element and suppose that climate predictions will require similar observations in the other tropical oceans (there is already some evidence) and also outside the tropics. For this reason, the OOSDP is recommending a level of support for Indian Ocean and Atlantic Ocean upper ocean temperature data, though this should be reviewed as further research is undertaken. There is also the additional important requirement to build a baseline of high-resolution upper ocean survey sections to monitor and understand upper ocean heat transport. Additional future, research, e.g., CLIVAR, will be critical for the development of an effective long-term strategy for subgoal 2c.

RECOMMENDATIONS FOR V.E

Elements of existing observing systems:

E1. Observational elements which might be deemed "operational" now are those that form part of the northwest Pacific upper ocean monitoring system currently operated by Japan. For example, measurements of the Far Seas Fisheries Fleet have been conducted routinely over a long period, are of good quality and have been relatively systematic. The value of these systems for monitoring and description has been demonstrated and their maintenance should be encouraged by the ocean observing system for climate.
The basis of a communications system (IGOSS) has been in existence for several years (see Annex II). Such a system must be maintained and substantially improved for the observing system (see Section VI).

Elements to be added now to complete the initial observing system:

E2. The existing broadcast mode XBT programs for the purposes of monitoring and understanding the subtropical oceanic heat budget and circulation and estimating air-sea heat fluxes on large scales.

E3. The existing TOGA VOS and TAO networks made operational (at close to present levels) for the purposes of ENSO monitoring and prediction.

E4. Routine XBT sampling from polar research and supply vessels.

E5. A global network of subsurface floats (e.g., ALACE) obtaining upper ocean profiles of temperature, and conductivity as feasible (see Sections V.D and V.I).

Enhancements to initial system:

E6. Increased TAO salinity measurements and XCTDs on selected VOS lines and polar research/supply vessels to enhance our knowledge of upper ocean salinity variability. The use of XCTDs should be increased as the device proves reliable.

E7. The operational implementation and maintenance of systems for monitoring and predicting regional ocean variability (e.g., in the Kuroshio).

E8. The existing, frequently repeated trans-equatorial sections, including enhanced (50 km or better) coverage in regions of persistent high gradients (boundary currents, fronts, or equatorial current systems).

E9. ADCP measurements on VOS as feasible and archived with ADCP measurements from research vessels.
E10. A minimal array of direct horizontal velocity measurements in the equatorial and surface boundary layers from moorings and drifters for the purposes of validating model simulations and predictions, especially for ENSO.

Research and development:
E11. Evaluation of the mix of altimeter, remotely sensed SST and subsurface data needed for initialization and validation of mid-latitude ocean prediction models.
E12. Re-evaluation of the tropical ocean sampling strategy in the light of knowledge obtained through the end of TOGA and the expected utilization of sub-surface data in climate prediction schemes.
E13. Cooperation in the scientific and economic evaluation of optimal sampling strategies for the tropical oceans and world ocean taking into account the variety of platforms available for the observing system and of model data assimilation systems.
E14. Consideration, in the light of WOCE and other climate research, of the implementation of selected high-density VOS XBT sampling lines in order to monitor, and assist in understanding, the transport of heat and mass in the upper ocean.
E15. Consideration of the operational implementation of new technologies in the light of experience from WOCE and other research programs.

## V.F. Sea Level

### V.F.1. Methods

Absolute sea level and its variability can be measured from space using altimeters, which provide global coverage, and in situ using tide gauges, which can provide high accuracy data at a fixed point (one inherent need is for the determination of altimeter bias and its possible drift). It is reasonable to expect that satellite altimetry data, often corrected and blended with in situ data, will become the working sea level data set and will be utilized by detection and prediction systems for climate variability at all time scales. The required mix of in situ and satellite measurements depends on the problem to be addressed and may change as experience is gained with satellite altimeter systems, including the analysis of their data.

Altimeters. There are two altimetric missions now flying. They are ERS-1 launched in 1991 with a repeat cycle of 35 days for most of its mission and an orbit that reaches latitudes of 82° and TOPEX/POSEIDON launched in the summer of 1992 with a repeat cycle of ten days and an orbit that reaches latitudes of 65°. Both the orbit tracking system accuracy and intrinsic altimeter precision of the TOPEX/POSEIDON mission are superior to that of ERS-1. The data from both missions is now being analyzed and their final accuracy after radial orbit error, atmospheric, and ionospheric corrections are now being determined. For TOPEX/POSEIDON overall rms uncertainty is expected to be below 5 cm and is now limited by tidal corrections applied. The current ERS-1 orbit accuracy obtained by combining ERS-1 and TOPEX/POSEIDON crossover measurements data sets is approaching 10 cm rms. TOPEX/POSEIDON data has illustrated the need for better open ocean tidal models if the full potential for the altimeter to define lower frequency sea level change is to be realized. However, TOPEX/POSEIDON is itself providing the information on open ocean tides that will lead to the development and validation of such tidal models. Much effort is underway in the research community to understand, validate, and improve methods used for assimilation of altimetric measures of sea surface height into ocean predictive models.

Koblinsky et al. (1992) recommend a program of multiple contemporaneous radar altimeters in order to ensure a continuous time series and to improve oceanographic sampling. At least one altimeter mission of TOPEX/POSEIDON accuracy should be in place at all times. Although two or more altimeters in complementary orbits are required to define the propagation of meso-scale eddies at mid-latitudes, the required accuracy of a second altimeter for this purpose alone is not so demanding. At this time, there is not a requirement for two altimeters as part of an ocean observing system for climate.

The determination of absolute ocean currents from satellite altimetry is limited by knowledge of the marine geoid which can be determined through a special gravity satellite mission.

In situ gauges. Figure V.F.1-1 (from IOC, 1991) shows the existing network of in situ sea level stations included in the Global Sea Level Observing System (GLOSS). The quality and frequency of reports from these stations varies greatly and many have been installed to meet the needs of coastal states for information on tides and sea level variations in local waters.

TOGA and WOCE have provided support to upgrade some 60 to 70 gauges which are a limited subset of the GLOSS stations. For TOGA, some of this subset provide observations of ENSO events in the tropical Pacific and for WOCE, measurements of sea-level changes across restricted regions and passages from which changes in transport may be inferred. About 50 of this subset, distributed globally, mostly on open ocean islands, provide information for the calibration and validation of satellite altimeter measured sea level. Initial indications from the analyses of TOPEX/POSEIDON measurements suggest that the requirement of tide gauges in support of future high-precision altimeter missions may be relaxed.

For the detection of decadal and longer changes in global sea level, a subset of the global sea level system, preferably with long consistent records, must be maintained. The accuracy and quality of the records are of paramount importance for such applications. The design of this network should take into consideration model predictions of the spatial structure of sea level change due to increasing greenhouse gases. To measure the change in ocean volume as predicted to arise from greenhouse gas warming, the network requires the establishment of an accurate controlled international earth reference system so that the locations of tide gauge sites and satellite tracking stations can be geocentrically positioned and corrected for tectonic motion. This requires a sufficient number of globally distributed permanent satellite tracking stations to maintain the reference system for the earth's center of mass. Tide gauges can be positioned in this system using very-long baseline interferometry (VLBI) and the GPS in differential or absolute mode. The number of tide gauges that must be positioned in this manner still needs to be determined, but is thought to be of order 50. While some number of tide gauge sites may serve both purposes, the tide gauges required in support of altimetry are not expected to be the same subset of GLOSS stations that is required for the detection of sea level change due to greenhouse gas warming.

## V.F.2. Observing system requirements for sea level

### RECOMMENDATIONS FOR V.F

Elements of existing observing systems:

F1. A subset of the GLOSS network, preferably with long consistent records.

F2. The TOPEX/POSEIDON and ERS satellite missions for precise global altimetry, which are not operational but meet the basic requirements for satellite altimetry.

F3. A subset of the existing TOGA tide gauge network in support of the observation of ENSO events. This requirement would be relaxed should future altimetric measurements of sea level be assured.

Elements to be added now to complete the initial observing system:

F4. A subset of the GLOSS sea level stations geocentrically located using GPS in a differential or absolute mode with VLBI. This requires maintenance of a terrestrial reference system.

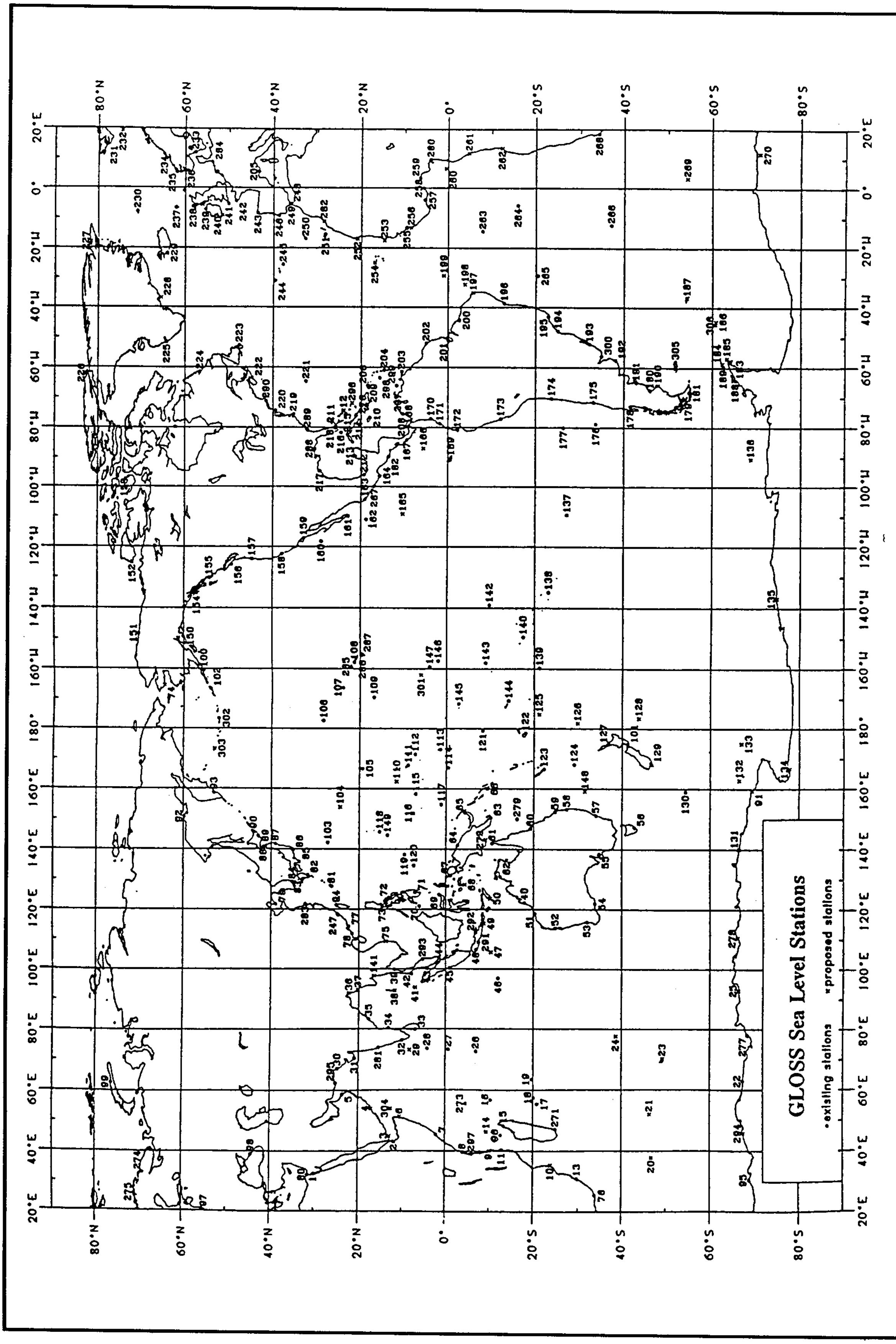



Figure V.F.1-1. Map of GLOSS sea level stations (from GLOSS, 1990).

These measurements will be used to detect changes in global sea level and as checks against model predictions.

F5. Fully operational long-term precision altimeter satellite missions and a yet to be determined number of precision, satellite-reporting sea level gauges, many on oceanic islands, in support of these altimeter missions. Given the long advance time required to plan and prepare satellite missions, it is essential that efforts be made now to ensure that continuous coverage is available after the ERS and TOPEX/POSEIDON missions.

Enhancements to the initial system:

F6. A specific satellite mission to determine the Earth's gravitational field and marine geoid in order to permit the accurate estimation of the absolute ocean circulation from radar altimetry.

## V.G. Sea Ice

### V.G.1. Methods

Sea ice extent and concentration. The best estimates of time and space scales of variability of sea ice extent are derived largely from space-borne remote sensors, a limited number of under-ice platforms, research stations, and ice breaker and submarine cruises. Satellite sensors provide the practical basis for measuring sea ice extent and concentration. In particular, passive microwave imagers (electronic scanning microwave radiometer (ESMR), SSM/I, and SMMR) dating back to 1973 are compiling an historical record of low resolution (25-30 km) estimates of first and multi-year sea ice concentrations and of ice free areas.

Using passive microwave radiometers, sea ice extent can usually be located with an accuracy of about 30 km through maps of brightness temperature (Parkinson et al., 1987; Gloerson et al., 1992). At the present time the SSMI aboard the DMSP satellite provides global coverage with a repeat cycle of approximately three days, which results in frequent coverage of polar regions. For operational applications, these data are transmitted to the NOAA Ice Center where they constitute the main input to weekly analysis charts of ice concentration, type, and extent. The brightness temperatures and derived ice concentrations are archived and made available for research purposes.

Although ice concentration and the fractional area of ice types such as "first year" and "multi-year" ice are estimated using SSMI observations, the accuracy and interpretation of these estimates is uncertain because the brightness temperatures are affected by properties of ice and snow, and of the intervening atmosphere, in addition to those directly related to ice type and concentration. For example, during the summer season melt water ponds have approximately the same signature as open water in the applicable wave bands. The various algorithms that are presently being used by different groups for estimating ice concentration from microwave data can give radically different results. Needed are measurements of the fraction of open water in the interior of the Arctic ice pack to an accuracy of perhaps 2% in winter and 5% in summer. In the Antarctic, a winter accuracy of 5% would be adequate. There is no immediate prospect of measuring sea ice concentration to this accuracy.

Important thermodynamic processes associated with sea ice formation and melting often occur on rather small scales of the order of 100 m to 10 km in leads and polynyas. Observations of these features from satellites require spatial resolution not obtainable from the passive microwave sensors used for global observations of sea ice extent. However, these processes need not be observed globally, and active radar, particularly synthetic aperture radar (SAR), capable of resolving these features on time scales of several days and spatial scales of 100 m to 100 km may be used over limited regions.

Sea ice thickness. Sea ice models used in conjunction with atmospheric and oceanic circulation models for the investigation of large scale and long-term climate problems should account for both thermodynamic and dynamic processes. The most important sea-ice variable for the discrimination between different dynamical parameterizations is the sea-ice thickness. Very limited thickness data are available for the Arctic, even fewer for the Antarctic. The thickness data set has to be improved considerably to allow for proper model verification. For the validation and development of dynamic portions of sea ice models, data on ice movement are also required. Routine estimates of sea ice movement can be made using sequences of satellite images and through the use of drifting buoy networks.

We have no way at present to directly measure ice thickness using satellite data; hence, we are not able to monitor global variation in sea-ice volume. Satellites only sense radiation emitted or scattered from the top surface, or the volume of the top few tens of centimeters, of the ice. Satellite researchers on sea ice are attempting to relate these surface radiative properties to ice thickness through a mixture of physics and empiricism, often through the intermediary of "ice type"—new, first-year, or multi-year ice. A review of approaches is included in the report of a sea ice thickness workshop held in November 1991 in Maryland and edited by Thorndike et al. (1992).

There are three potential techniques for estimating ice thickness using satellite data. Two involve microwave; the third uses AVHRR. The microwave methods are described in the book entitled "Microwave Remote Sensing of Sea Ice", editor Frank Carsey, Geophysical Monograph 68, American Geophysical Union, 1992. Chapter 5 describes the radar signatures of different ice types, which permit a rough discrimination between different ice thicknesses based on the surface roughness. Second, passive microwave algorithms, as described in Chapter 23, allow discrimination among open water, first-year ice, and multi-year ice, which again provides a crude discriminator of ice thickness. Third, using the thermal infra-red channels on the AVHRR allows determination of ice surface temperature to within about 1°C. If we obtain ice surface temperature, and we know the air temperature from meteorological stations or buoys, then ice thickness can be estimated from a thermal balance (Lindsay and Rothrock, 1993).

Ice thickness can be estimated by drilling holes through the ice, by tracked drifting buoys using thermistor chains (under development), by submerged moored buoys with upward looking sonar, by airborne laser profilometry and electromagnetic techniques, by ice breaker cruises, and by sonar measurements from submarines. The coverage by such techniques is limited in spatial and temporal extent, but every effort should be made to assemble and compile all existing and future data.

Sea ice velocity. Ice motion in response to wind and currents plays a major role in determining the ice thickness distribution and ice edge location. Divergent ice motion produces open water, thereby enhancing the rate of ice production during the winter, and convergent motion deforms and thickens the pack by rafting and ridge-building.

Ice thickness and motion together determine the transport of ice mass, and therefore of latent heat, salt, and fresh water. To document and understand the role of the Arctic Ocean in global climate, it is essential to monitor the advection of sea ice both within the Basin itself and across its margins at Fram Strait. Ice export through Fram Strait represents the largest input of freshwater to the Greenland and Iceland Seas, where salinity stratification is closely tied to deep convective activity. Around the Antarctic, divergence results in a net northerly ice transport: regions closer to the coast, and particularly the coastal polynyas (e.g., Smith et al., 1990), are regions of high ice production and more northerly regions are areas of high melt. Ice advection changes what would otherwise be a seasonal cycle of melt and freezing into significant regional variations in heat and buoyancy fluxes.

Ice velocity data are necessary to verify sea ice models and, since ice motion provides the mechanical forcing for the ice-covered ocean, can be used to drive ocean models.

Surface albedo. The surface albedo of ice covered seas is crucial to climate feedbacks that play a major role in amplifying surface warming. For snow-free ice the albedo is a function of ice thickness (e.g., Allison et al., 1993), while for snow covered ice the albedo depends upon the snow properties.

When the sky is clear, average albedo over sea ice can be estimated from visible channel data of AVHRR satellite imagery, with a resolution of approximately 1 km. Further research is required to determine whether spatial fields of average surface albedo could be analyzed on a routine basis from a combination of simultaneous SSM/I and AVHRR data, or other remote sensing data.

V.G.2. Observing system requirements for sea ice

A thin body of data has been accumulated in the Arctic sufficient for a first assessment of the broad-scale spatial and seasonal climatology of ice thickness that can be used for model validation. This is not true for the Antarctic. To establish the broad climatic pattern of Antarctic ice thickness, at its simplest, would require estimation of :

- open water fraction
- thin ice (< 0.3 m) fraction
- typical un-ridged ice fraction and mean thickness
- ridged ice fraction and mean thickness

at a 500 x 500 km grid resolution for each month of the year. SCAR, as part of the GLOCHANT program, is presently establishing a standardized and quantified reporting scheme for use by vessels in the Antarctic and WCRP has proposed a program of ULS moorings: both projects will contribute to this requirement.

RECOMMENDATIONS FOR V.G

Elements of existing observing systems:

G1. Monitoring of the extent and concentration of sea ice using both passive and active microwave sensors globally and synthetic aperture radar in specific regions.

Elements to be added now to complete the initial observing system:

G2. Maintenance and optimization of the Arctic and Antarctic drifting buoy networks.

G3. Enhancement of existing research networks using in situ measurements to estimate ice thickness regionally, including possible declassification of submarine data and future submarine sections under sea ice.

Enhancement to initial system:

G4. Determination of ice velocity fields from SAR/AVHRR and buoys on a routine basis as required to improve dynamic ice models and to provide forcing of the ice-covered ocean in ocean models.

Research and development:

G5. Improvement of the utilization of satellite data in automated analyses and the incorporation of fractional ice cover and ice dynamics into global circulation models.

G6. The improvement of algorithms for estimating global sea ice concentrations from passive microwave sensors by using data assimilation techniques and comparison to sensors with higher spatial resolution.

G7. Research to enable estimation of the spatial fields of surface albedo from satellite sensors on a regular basis.

G8. Research and development of operational methods for sea ice thickness determination; in particular, by enhancing the Antarctic ice thickness monitoring project.

## V.H. Carbon

### V.H.1. Strategy and measurement techniques

Absorption of atmospheric $CO_2$ by the oceans is controlled by the physical and biological pumps. The efficiency of these pumps may change significantly over the next decades as a response to climate change and alter the net carbon uptake by the oceans. In the long term, development of the ocean observing system for climate will have to consider the problem of detecting these changes. At present, our knowledge is insufficient to firmly establish the best strategy to observe these changes. WOCE and JGOFS will provide information for the refinement of the strategy.

In the short term, the strategy should be to obtain in situ measurements of upper ocean properties ($pCO_2$, temperature, chlorophyll) with the global coverage of satellite observations of SST, wind velocity, and ocean color. This is essential to establish transfer functions for different times and regions of the globe to estimate fluxes. Fluxes are essential for the validation of global inverse atmospheric models and ocean models used to project the evolution of oceanic $CO_2$ uptake, and consequently the evolution of the atmospheric $CO_2$ concentration. The inventory, and its changes, of the total $CO_2$ in the water column provides a means to check these projections of oceanic uptake. Inventories can be obtained from large-scale surveys at regular intervals. Surface winter data are critical to fill gaps in the direct estimation of $CO_2$ uptake by the ocean and for the validation of models. In addition, a selected number of time series measurements of carbon components through the entire ocean column are needed to resolve short term variability and to put the inventories in context.

Present status and methods. At this time, $pCO_2$ and total $CO_2$ measurements in seawater have respectively reached accuracies about $\pm$ 2-3 µatm and $\pm$ 2 µmol/Kg. The major problem to date is intercalibration among different investigators. An international intercalibration effort is underway to resolve this problem. Now, $pCO_2$, and total $CO_2$ measurements can be done routinely with a single technician aboard VOS. Unattended sensors are under development for use on VOS and also for deployment on drifting buoys.

Continuous fluorescence monitoring on ships has been done routinely since the early 1970s. Bio-optical packages have been deployed on fixed moorings (for up to six months) and very recently on drifting buoys.

The measurement of $^{13}C/^{12}C$ is not yet widespread, but collection of samples can be routinely carried out on VOS. It should be possible to achieve an accuracy of $\pm$ 0.04 per mil; standards need to be developed for comparison between laboratories.

Ships. Research vessels are able to obtain the complete suite of measurements needed to determine $CO_2$ fluxes and carbon inventories. The data from ships are potentially of the highest quality and level of detail. On WOCE cruises, $pCO_2$, total $CO_2$ and alkalinity are measured routinely on all the WOCE lines. Furthermore, in certain cases photosynthetically available radiation and fluorescence are measured as well. This program will continue at least through 1997. The carbon system variables are measured on all JGOFS cruises along with detailed biogeochemical parameters. This will provide background for the development of transfer functions and eventually dynamic biogeochemical models.

However, the coverage from scientific vessels (e.g., as part of the WOCE and JGOFS programs) alone cannot resolve all the relevant scales of variability. The situation can be improved with equipped VOS; however, VOS ships sample only the surface layer and their spatial coverage is limited to shipping lanes.

Buoys. Drifting buoys equipped with $pCO_2$ sensors, fluorometers and thermistors are required for global satellite ocean color measurements. Lagrangian buoys equipped with drogues can yield time series of measurements within defined water masses. This is important for the development of time-dependent algorithms linking biological and chemical processes (see Taylor et al., 1991). In addition, buoys complement ship (scientific and VOS) coverage in areas and seasons where ships are not present.

Satellites. Satellite measurements of ocean color provide global scale coverage of phytoplankton biomass. Experience with the coastal zone color scanner (CZCS) sensor has shown that it is possible to estimate phytoplankton biomass from ocean color, at least in open ocean waters. Introduction of the new sea-viewing wide field sensors (SeaWiFS) and of its successors will considerably improve the sensitivity and accuracy of chlorophyll estimates. These data are central to establishing and using transfer functions for the extrapolation of in situ surface measurements of $pCO_2$ and $CO_2$ fluxes to regional and global scales. Satellite measurements of SST and of the surface wind field are also used in the transfer functions and are thus necessary complementary measurements.

Time series. The possibility that time series of hydrographic, chemical and biological measurements at fixed locations can be used as a monitoring tool in the context of the observing system should be seriously considered. Some long series exist (e.g., station P, CalCOFI and continuous plankton recorder (CPR)). Except for station P, in the subpolar Pacific, measurements to date have usually been of hydrographic and biological variables. Chemical variables, particularly with respect to the carbon system, have not been routinely measured. Inclusion of such measurements is necessary in the context of monitoring climate change within an observing system. The sites in use now are not necessarily the best ones with respect to the signal/noise ratio, but they are the only long time series in existence and are providing invaluable information on the natural variability of the ocean at long time scales.

Within the past five years, the JGOFS program has established new time series stations near Bermuda and Hawaii with the specific goal to study the variability of biogeochemical processes in the ocean interior. The establishment of additional JGOFS-type time series in other oceanic regimes in the near future is to be encouraged. Results from the study of data from time series stations should help design observing strategies for the ocean interior, particularly with respect to the sampling frequency required to resolve the climatic signal. The sampling strategy for the observing system will be heavily dependent on the results of WOCE and JGOFS.

Dimethyl sulfide. The complexity of the cycles of production and consumption of dimethyl sulfide in seawater and its chemical transformations in the atmosphere point to the need for integrated field experiments that simultaneously examine the major controlling factors in both water and air (Malin et al., 1992).

V.H.2. Observing system requirements for carbon

RECOMMENDATIONS FOR V.H

There is no existing observing system.

Elements to be added now to complete the initial observing system:

H1. Maintenance of existing VOS lines that carry a technician making $pCO_2$ measurements in the surface waters, with the addition of other VOS lines on which are measured $pCO_2$ and fluorescence as feasible. Where possible, the $pCO_2$ measurements should be accompanied by the analysis of $^{13}C/^{12}C$ in the $CO_2$ of discrete samples.

Enhancements to initial system:

H2. Completion of the development and deployment of unattended $pCO_2$ sensors with data transmission via satellite which can be used on VOS and allow complete autonomy of the system. Such unattended $pCO_2$ measurements have recently begun in the North Atlantic and, when this development is complete, the new system should replace the manned systems on VOS supported by the observing system. Development of automated sampling techniques will be needed to continue isotopic ratio measurements on VOS.

H3. A continuing series of satellite missions retrieving ocean color measurements. The SeaWiFS ocean color sensor is scheduled to be launched in late 1995; it should be followed in 1996 by other satellites (Ocean Color and Temperature Sensor (OCTS) on ADEOS, EOS Color, Moderate-Resolution Imaging Spectrometer (MODIS) and MERIS on next generation polar platforms). When the development of the surface drifters with the capability to measure $pCO_2$ and fluorescence is complete and they are tested, arrays of these drifters should be deployed under SeaWiFS tracks for calibration of the satellite sensors. These deployments should be designed also to complement the VOS series; for example, they should be deployed in high latitude areas.

Research and development:

H4. The short-term observing system strategy is oriented toward interpolation of surface data and validation of inverse atmospheric and three-dimensional oceanic models. The long-term goal must be to move toward better three-dimensional physical-biogeochemical models that can assimilate data from the carbon observing system.

H5. Some long series of hydrographic, chemical, and biological measurements exist (e.g., CalCOFI). Within the past five years, JGOFS has established new time series stations near Bermuda and Hawaii to study the variability of biogeochemical processes in the oceanic interior. Results from the study of these data should provide a guide to the design of observing stations for the ocean interior, particularly with respect to sampling frequency required to resolve long term variability. Assess the use of time series of hydrographic, chemical, and biological measurements at fixed locations as possible observing system monitoring tools.

H6. The acquisition of a global, high-quality data set of total $CO_2$, total alkalinity and hydrographic data is underway during the 1990s through a joint effort by WOCE and JGOFS. Some of the WOCE lines should be repeated. With our present measurement accuracies, a time interval of approximately 10 years for the repeat sections is recommended. The choice of the lines should be based principally on data obtained by WOCE and JGOFS, considering also data from Geochemical Ocean Section Study (GEOSECS) and other earlier surveys.

H7. A global network of stations as part of the observing system might be built as an extension of the present Australian station at Cape Grim, Tasmania and those to be established by NOAA in the northern hemisphere, upwind and downwind of the North American continent. An expanded network, including volunteer observing ships, could monitor property changes in dimethyl sulfide and aerosol particles on seasonal and decadal time scales, using current technology to automate many measurements (Bates, 1992). In contrast to $CO_2$, the turnover time of dimethyl sulfide in the atmosphere is fast (days). Hence, monitoring of changes in atmospheric dimethyl sulfide should be on meso-scales.

## V.I. Measures of Ocean Circulation in Relation to Climate

### V.I.1. Introduction

The conditioning of ocean waters at the surface and their subsequent sinking and circulation is forced by exchanges with the atmosphere. We know that this results in the global redistribution and storage of heat, fresh water, carbon and other climate-related variables.

Based on scientific principles, we are confident that these exchanges, both between atmosphere and ocean and between the upper ocean and its interior, will affect earth's climate. However, models do not yet allow realistic simulations/predictions of these effects for prescribed forcing. In large measure this seems due to the lack of data adequate to verify/improve/constrain the models.

Many types/mechanisms of coupling between the ocean and atmosphere may result in significant atmospheric variability on climate scales. However, only few examples are yet known. One is the coupling between the upper tropical Pacific Ocean and the global atmosphere, known as the ENSO phenomena, occurring aperiodically on time scales from two to seven years and affecting global rainfall and temperature patterns.

Another example is the relation between multi-decadal SST signals in the subpolar North Atlantic and the signal in sea level pressure and winds over the high latitudes Atlantic (Kushnir, 1994). Kushnir provides empirical evidence to support the role of the thermohaline circulation in the evolution of the SST fields. Modeling evidence for coupling between subpolar surface conditions and multi-decadal variability in the overturning ocean circulation is given by Delworth et al. (1993).

SSS patterns also play an important role in the consequences of air-sea interaction. In the Labrador Sea, decreases in surface salinity has been observed to reduce convective rates and production of LSDW (The Great Salinity Anomaly, Dickson et al., 1988). Reduction of surface salinity leads to a cessation of convection followed by slow diffusion until stratification is reduced. Then, with conditions of adequate surface cooling, convection can penetrate rapidly to great depth. This "cycle" is likely tied to regional climate by one or more feedback loops, such as that proposed by Mysak et al. (1990), based on several factors including Arctic cyclogenesis, runoff, sea ice, surface salinity and regional circulation patterns. The Arctic and Greenland seas could have resulting climate oscillations of 15-20 years.

Given our present knowledge, what are the implications of such couplings for the design of an ocean observing system for climate?

First, ocean measurements are needed to improve the prediction of those coupled phenomena of climate import that have been demonstrated by research to have some useful level of predictability. The notable example is ENSO (Section V.E). The study of predictability and prediction of other coupled climate phenomena remains for now the domain of research; the CLIVAR program is being formulated with this intent.

Second, ocean measurements should be made to monitor production rates of the principal deep and bottom waters and to detect changes in such production and in the global inventories of climate-related variables (introduced to the ocean at the sea surface and transported by ocean circulation). These observations should be sufficient to track the climate state of the interior ocean. They must both be interpreted/evaluated in the context of models and be used in further model development (ocean and coupled ocean-atmosphere simulations).

Third, ocean data are needed to improve and constrain operational ocean models and future ocean-atmosphere models should be included in the observing system. The general circulation, particularly of the upper ocean is driven by momentum exchange via wind stress. This circulation can be simulated rather well by models given accurate long term, distributions of surface wind stress. Model improvements will require improved model physics (e.g., dissipative mechanisms), improved long-term global wind stress and surface flux fields, and measurements for model verification and data-based models. For verification, data are needed describing the strength (e.g., available potential energy) and configuration of the major ocean gyres, including the position and transports of principal ocean currents. The most effective approach to obtaining such descriptions is via precise satellite altimetry, and these data can be assimilated into operational ocean circulation models. However, the measurements required for periodically assessing ocean inventories of climate variables should also produce estimates of strength and locations of major gyres and currents, and so be used in model work. For model verification and data based models observations are needed of the internal distributions of temperature, salinity, and velocity.

Fourth, surface boundary conditions are needed (e.g., wind stress, SST, heat and freshwater fluxes). These requirements have been discussed in Sections IV.A, IV.B, and V.A-C. However, bottom boundary conditions also must be considered. Present basin- to global-scale simulations of ocean circulation use horizontal grids as small as 15-20 km at high latitudes. The grid size has been decreasing with the use of more powerful computers. It is clear that over much of the ocean we have little knowledge of bathymetry on comparable space scales.

### V.I.2. Repeat transocean sections

A major part of WOCE is devoted to carrying out a global survey of ocean properties via a one-time WOCE Hydrographic Program (WHP). As an adjunct to the WHP, the international $CO_2$ program is making measurements through the water column on WHP cruises. In the Pacific Ocean measurements are being made (at nominal station spacing of 30 n. mi.) along the tracks shown in Figure V.I.2-1; the survey tracks in the Indian Ocean shown in Figure V.I.2-2 will be occupied in 1995; and the Atlantic will be even more intensively surveyed. Thus, a good baseline for global ocean property inventories will result from WOCE.

The Atlantic Ocean has been the site of earlier surveys (though not so intensive in coverage or complete in properties measured) in 1957 during the International Geophysical Year, and in the 1980s by the Long Lines consortium and by the Transient Tracers in the Ocean program. It is clear from preliminary comparisons of WOCE and earlier data in the Atlantic that significant changes in properties or volumes of the water masses present (and so in heat and salt content) occur over decade scales (e.g., Levitus, 1989a, c) and longer (e.g., 35-year warming at 24°N as observed by Parrilla et al., 1994).

WOCE and JGOFS, with emphasis on the carbon cycle, will provide a global base line of property distributions. To monitor the long-term changes in those inventories of climate-related elements, repeated sampling on transoceanic sections at regular intervals will be required as part of the observing system. Salt and temperature should be measured as functions of pressure to the bottom. At this time CTDs and water samplers would be the technology of choice; technological developments, such as the Fast Hydrographic Profiler or Slocum, may offer future options. Selected stations should be sampled for selected tracers from small water volumes, with the objective of estimating time scales of renewal of deep and mode waters. Measurements to reassess carbon inventories, and their changes, must be included.

Sampling should be based on results of ongoing research on global distributions, inventories and models. Such transocean sections probably should cross each of the major subtropical and subpolar gyres as well as sampling the equatorial zone and Southern Ocean. East-west sections that cross Pacific, Atlantic and Indian oceans from continent to continent also are required for meridional heat flux estimates and data-based models (see Section V.D).

To assess the representativeness of measurements made at a given time on a transocean section, it is necessary to have knowledge of the variability on that section. Without estimates of such variability, based on repeated measurements, one cannot quantitatively assess to what extent changes between measurements of a transocean section in 1980, 1990, and 2000 represent decadal change versus random interannual variability. Therefore, it should be the domain of an ocean research program to establish the representative year-to-year variability of climate variables on transocean sections to be periodically repeated as part of the observing system. An example of the

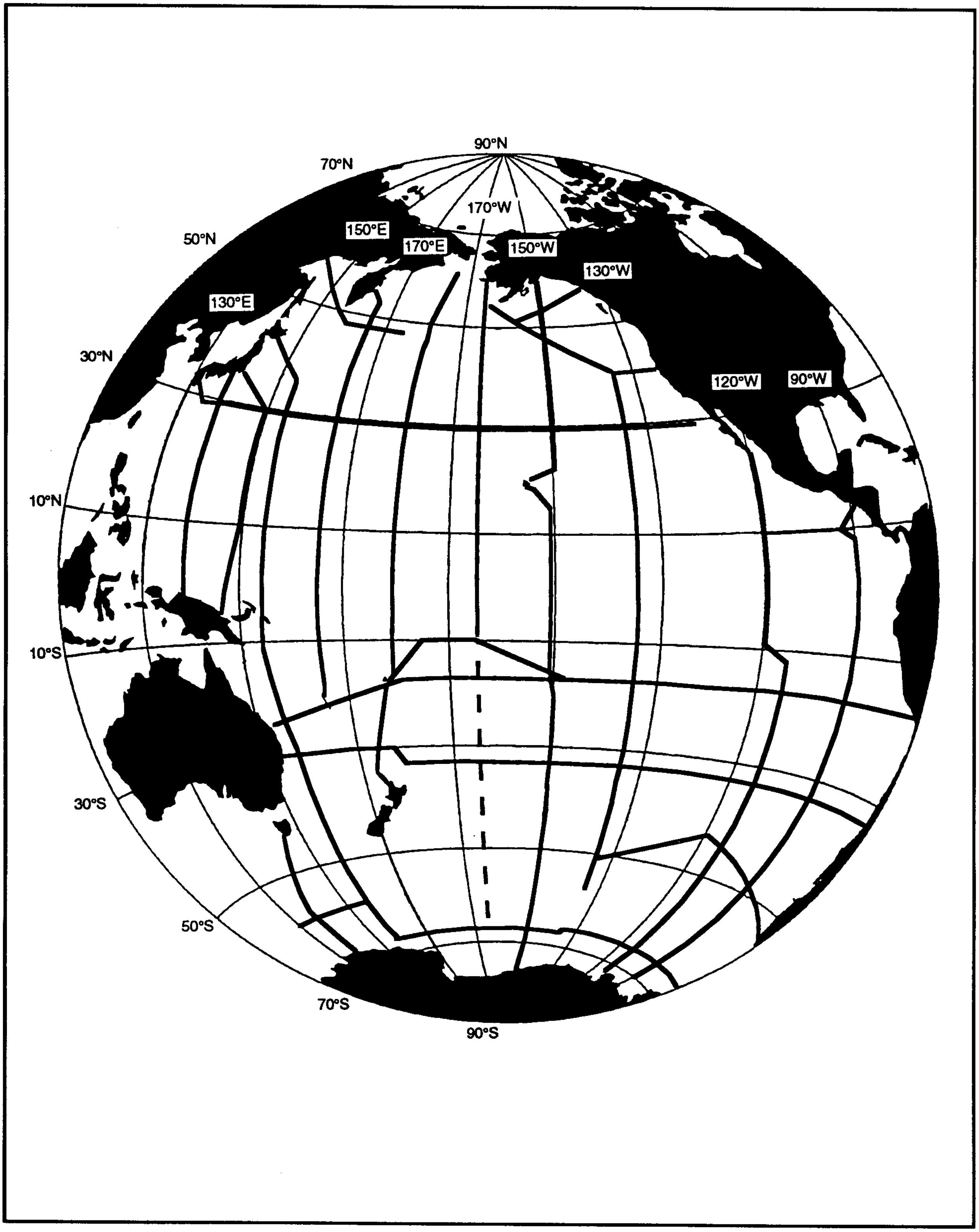



Figure V.I.2-1. WOCE one-time hydrographic sections in the Pacific during the early 1990s (the dashed line indicates a section to be done in 1996). Carbon components were measured and subsurface (1000 m) floats were released on most legs.

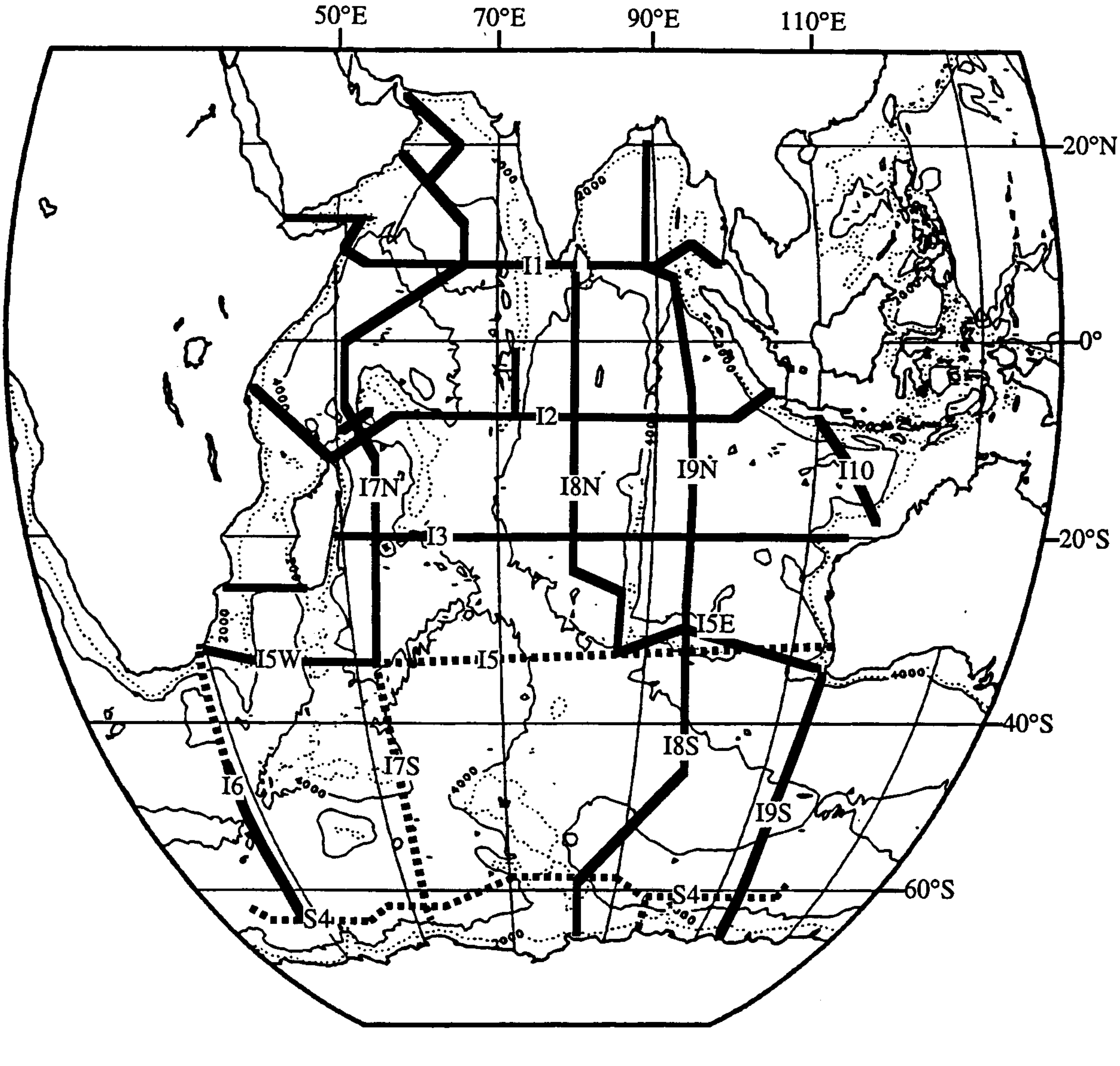



Figure V.I.2-2. WOCE one-time hydrographic sections to be carried out 1994-1995 in the Indian Ocean. Carbon components will be measured and subsurface (1000 m) floats released on most legs. It is intended that dashed lines will be carried out in 1996-1997.

necessary sampling and analysis is given by Roemmich and Cornuelle (1990) who have sampled repeatedly using high-resolution XBT/XCTD drops along the WHP line P14C from Fiji to New Zealand.

## V.I.3. Other in situ time series

Several research programs for regional to global scale monitoring of the upper ocean have been initiated (e.g., by various navies, TOGA and WOCE). One such is the program of upper ocean XBT observations made from VOS; the ship track distribution is shown in Figure V.I.3-1, where heavy solid lines denote repeat mode sampling and light lines denote broadcast mode sampling. The requirements to continue this network for upper ocean thermal data and to augment it for salinity measures are discussed in sections IV.B, IV.E, V.E, and V.D. Moreover, the repeat mode lines include mixtures of XCTD and XBTs to produce data in some cases adequate to establish the variability expected on hydrographic sections taken at those locations (see previous subsection).

Another research network consists of using the autonomous profilers, called ALACEs, to provide cost-effective vertical profiles of temperature and horizontal velocity measures at a subsurface depth (~1000 m) over the global ocean. ALACE is a neutrally buoyant float that can rise periodically to the surface and transmit information collected via Argos; lifetime depends on the frequency of vertical cycling, but can be five years for biweekly cycling. A version capable of measuring salinity is being tested. For more information, see Section VII.B.2.

Japan has long maintained an operational observing network consisting of surface and upper ocean measurements (including repeat stations and ADCP) near their islands. In addition, they use ship drift and surface drifter data to produce routine operational products for weather forecasting, fisheries, marine safety, etc. (e.g., see Figure I.B.1-1). Figure V.I.3-2 indicates the approximate area of analyses and forecasts.

Likewise, research monitoring has been initiated at selected locations or of specific phenomena. Required for the ocean observing system for climate are the continuation of efforts directed at monitoring water mass formation rates, the strength of major ocean circulation features, and information needed to interpret repeat transocean sections. One suite of measurements being taken annually to monitor water mass formation are repeat hydrographic stations across the southeast Labrador Sea and along the Greenland, Iceland, Faeroe, Shetland Ridge (shown in Figure V.I.3-2). These measurements describe the characteristics of LSDW formed during the previous winter and characterize the middle and bottom NADW flowing over the Iceland-Shetland Ridge system from the Iceland and Norwegian seas.

A series of measurements to monitor outflow of Mediterranean Sea deep water should be considered, because that basin provides salty water mass necessary for the present day processes of North Atlantic deep water formation. Other sites can be envisioned as well, and should be considered via research programs. An example is the Indonesian throughflow from Pacific to Indian Ocean where various strategies for monitoring are being pursued as part of WOCE. In WOCE, arrays of subsurface current meter moorings are being deployed to determine the circulation where it is topographically constrained (e.g., deep western boundary currents along New Zealand in the South Pacific and across the Indian Ocean at 20°S).

A few long-term, full-depth times series are ongoing with research support. Shown in Figure V.I.3-2, they are located off Hawaii, Bermuda, and Canary Islands. The Canary-Bermuda pair may be used as an indicator of the North Atlantic subtropical gyre strength; together with a trial station off California, the Hawaii station similarly could characterize the eastern North Pacific subtropical gyre. The Bermuda and Hawaii stations include, in addition to traditional hydrographic measurements, a suite of biogeochemical measurements intended to assist in the interpretation of carbon cycle measurements.

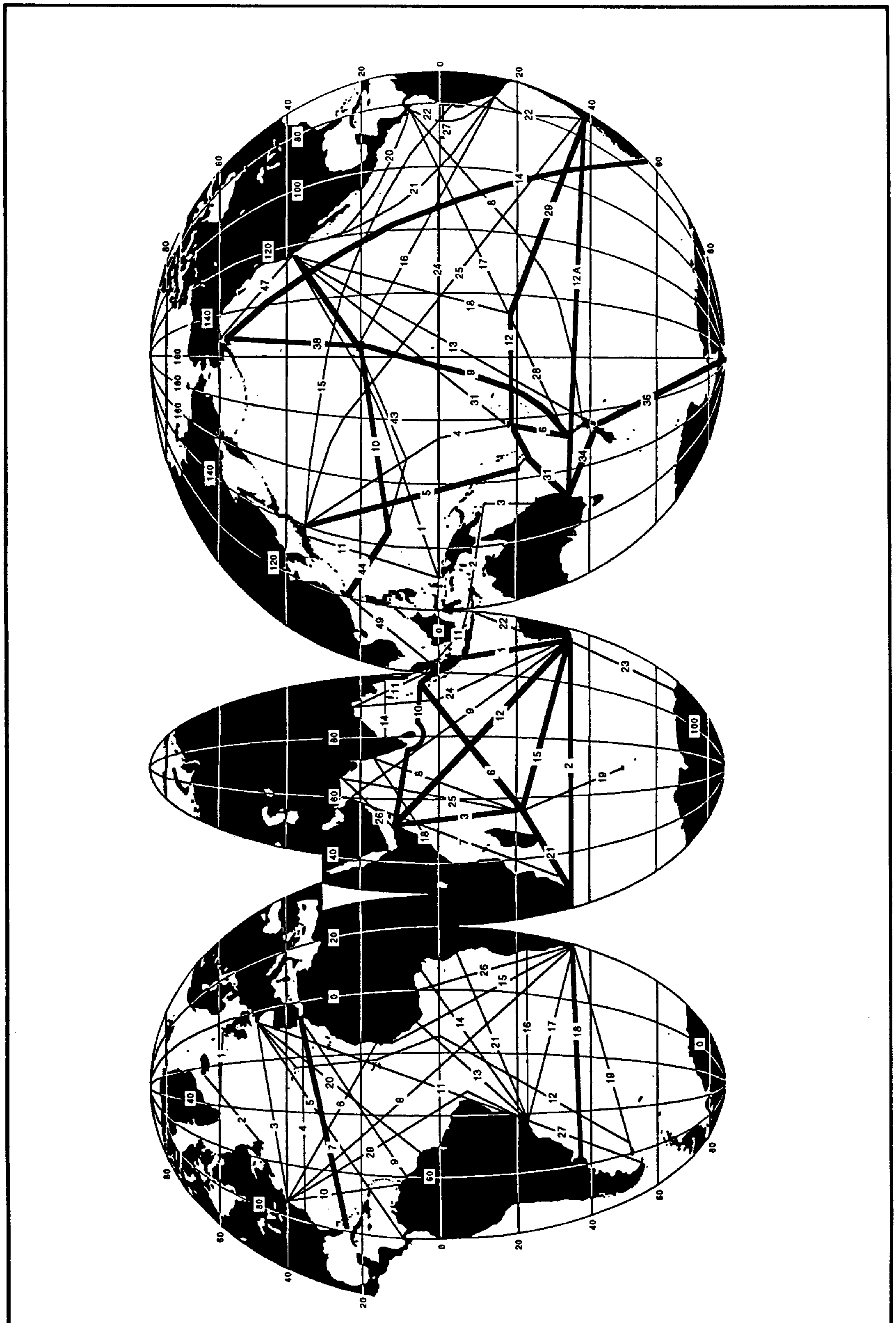


Figure V.I.3-1. TOGA-WOCE XBT lines on VOS. Heavy solid lines indicated planned high-density mode; other lines are sampled in broadcast mode.

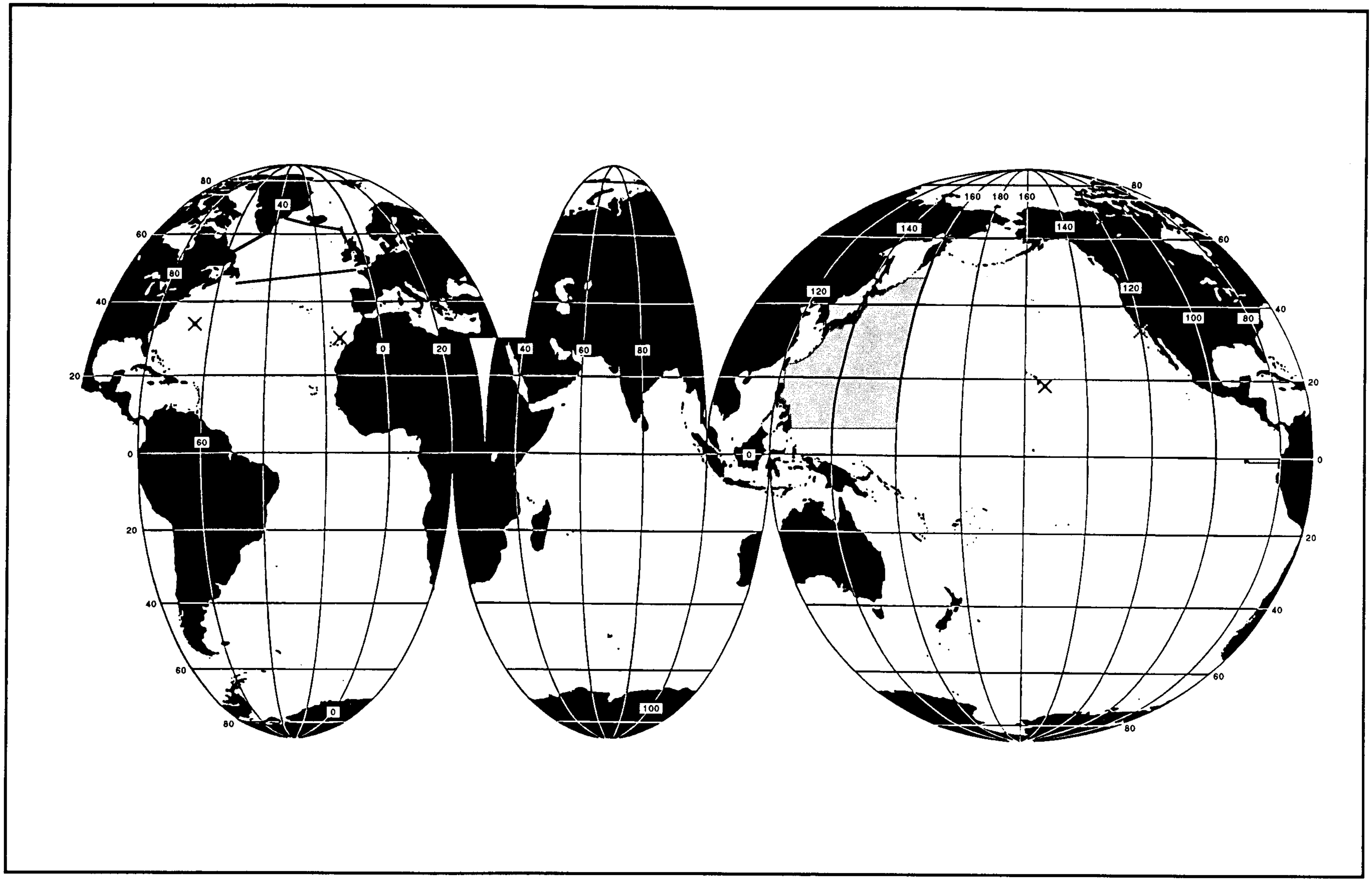


Figure V.I.3-2. Locations of long time series measurements underway. Stations off Bermuda, California, Hawaii, and Canary Islands are indicated by Xs. Lines indicate hydrographic repeat sections. Dotted shading indicates area of Japanese operational observing network.

As changes are made to the ocean observing system either because of changes in technology or resources, special attention should be given to continuing the limited number of existing time series measurements. Examples include XBT and hydrographic sections in the west Pacific, some of long (greater than 10 years) duration, the Panuliris Station ("S") at Bermuda, and other ocean stations now being occupied as part of WOCE and JGOFS. The decision to remove many of the Ocean Weather Stations, dictated by economic considerations at the time, led to the termination of oceanographic time series which still provide unique records of ocean variability. Considering, for example, the proven value of the data from Ocean Weather Station Bravo in studying interdecadal variability of the thermohaline circulation in the Labrador Sea (Lazier, 1980), consideration should be given for renewed occupation of this and other selected ocean weather stations. This might be accomplished through the use of new (probably moored) instruments and technology. There will be gaps in the time series but long-term series are extremely valuable.

### V.I.4. Global monitoring from space

Precise global measurements of sea surface height by satellite radar altimetry is now a proven method for monitoring the general ocean circulation and its variability. These data, together with an improved geoid, can be used to validate and constrain climate ocean models as mentioned in Section V.I.1 and elsewhere in this document. In addition, these measurements will support many OOSDP subgoals in addition to subgoal 3b.

### V.I.5. Compilation of research data

Most of the information necessary to develop realistic ocean simulation models must come from research programs, especially those of the WCRP. The observing system could assist in this effort by providing a baseline of ocean data (e.g., Section V.E.2, subgoal 2a), by compiling selected research data, and producing needed climatological products.

As one example, using all of the direct current measurements available to the international research community at the time, Dickson (1989) prepared a global summary of the statistics (mean and eddy kinetic energy) of deep ocean currents. He placed emphasis on data available at 4000 m and recommended continued measurements at that depth. Efforts should be made to obtain access to additional data sets from sources not now available to the research community, with the assurance that the information be released only in the form of additions to the climatology. The next compilation should be made in the early 2000s, when the complete WOCE data sets will be available. Included should be velocities at other levels, especially for the 1000 m level based on ALACE and other subsurface floats, and for the surface based on observations of the WCRP surface velocity program. Thereafter, compilations should be made at regular intervals.

### RECOMMENDATIONS FOR V.I

Elements of the existing observing system:

I1. The long-term observational networks of Japan, Russia, and other nations.

Elements to be added now to complete the initial observing system:

I2. Establishment of long-term support for selected observing elements aimed at monitoring deep and bottom water renewal presently supported as research observing elements. Initially this is to be done by the use of repeat hydrographic sections in critical regions.

I3. Assembly in one archive of measurements and estimates of ocean velocity and other key properties being gathered as part of research or operational programs and their use in the compilation of a climatology of ocean velocities. It is recommended that such data be assembled from multiple levels within the water column. Initially, velocity statistics should be compiled from the surface, 1000 m, and 4000 m.

I4. Precision satellite altimetry (see Section V.F).

I5. Operational support for existing long time series stations of potential significance to establishing the climate record.
I6. A global network of subsurface floats (e.g., ALACE) obtaining profiles of temperature, and salinity as feasible (see Sections V.D and V.E).

Enhancements to initial system:
I7. Repeated sampling at regular intervals on transoceanic sections. These sections should measure temperature, salt, carbon, and selected tracers for renewal rates and measurements to reassess inventories of heat, fresh water, and carbon. The selection of sections should be based on the results of ongoing global inventories and models.
I8. Global satellite measurement of the marine geoid.

Research and development:
I9. Convene an international workshop to review the status of long time series and to examine existing time series data for their usefulness to climate studies.
I10. Development of techniques for the reoccupation of the Ocean Weather Station sites or others with long time series observations proven to have use in climate monitoring, detection, understanding, or prediction; and the deployment of such systems as feasible.
I11. Development of new approaches to effectively and economically monitor inter-basin and boundary current transports of key properties should be encouraged now. Likewise new approaches to regularly monitor the inventories of heat, available potential energy, tracers of water masses, and chemical species in the ocean are sought. Development and testing of several autonomous ocean CTD profilers are underway and should be encouraged and closely watched.
I12. Investigation of the possibility of monitoring water mass formation from space, as perhaps with SAR.
I13. As a particular approach to integral measurements of transports, concerted attention should be given to monitoring of voltages induced in submarine cables. The technique must be proven as a reliable diagnostic that can be credibly interpreted as transport. To be useful for long-term monitoring, the cables must be available where needed, on a long-term basis, and be affordable.
I14. Assessment of the horizontal scales on which ocean depth must be known for successful global ocean simulations.

## V.J. Models and the Observing System

The observing system, to have maximum impact, will need to make use of models in many different ways. At present the integration of models and observations is limited compared to what is possible and desirable. Circulation models, whether ocean or coupled ocean-atmosphere need to be validated against observing system analyses. The profitable feedback between models and data must be established to facilitate the use and evolution of the operating system. Here, it is only possible to describe some general characteristics of models that are in use in climate-related ocean work and to indicate how they are being used at present, and maybe in the future, to advance desired model-data interactions. In the longer term, it is the Panel's expectation that the benefits of this interaction will become so clear that the managers of the observing system will treat model-data interaction activities as a fundamental aspect of the system.

In essence, models are tools for interpolating and extrapolating information gathered by direct sampling, perhaps providing estimates of fields that are not readily observing directly. Models can include both deterministic and statistical methods.

Models can use knowledge of the physical, biogeochemical and/or cryospheric processes through their encapsulation in a set of mathematical equations. If information on actual conditions are provided as boundary or initial conditions for the equations, the equation solution uses this information to infer conditions remote from its source. For example, an ocean model forced at the surface by observed winds and heat flux will provide an estimate of subsurface temperature and currents. The accuracy of these estimates will depend on both the fidelity of the model and on the quality of the information provided to drive the model. If the forced system produces results that are known to be in error, it may be possible to correct the evolution/solution of the model by providing additional sources of information interior to the model domain. It may also be necessary to correct the model's parameterization of important processes. This model-data interaction should, in theory, provide a more useful product. NWP models are extremely skillful at short range forecasts (six to 24 hours) and the combination of data and model produces an analysis that is better than either system could produce alone. In this case, the analysis can be used as the initial conditions for a further forecast.

An alternative approach is to use statistical knowledge to create a stochastic model of the system. Past data are used to "teach" the model how to react under certain conditions. The model can interpolate information between locations (say to a regular grid) and extrapolate local information to a remote locations, or perhaps project the information into the future (a forecast). Such systems have been used for forecasting ENSO; they are also the basis for several analysis systems (e.g., the NMC SST analysis).

This section starts with a short overview of the state of modeling of relevance to the observing system. For guidance through the discussion, Figure V.J-1 shows schematically several different ways of integrating the model and observing elements. We address some aspects of how models can be used in simple ways for the observing system design. Next, some aspects of how model-data integration is addressed via sequential data assimilation procedures is described. Lastly, some remarks are made about inverse methods, in which model results and observations are blended, in an iterative process, until specified minimization constraints are satisfied. At present, thoughtful inversions appear to offer the best prospect for optimal data-model integration.

### V.J.1. Existing models and their roles

The simplest models of use to the observing system are mapping and sampling algorithms based on objective interpolation. This formalism was discussed in Section III.D. Much of the work of OOSDP has been to assemble the best available information about space and time correlation scales for the climatically important variables. Most of the subsurface ocean fields and many of the surface fields available for climate study at this time have been prepared by some sort of subjective or objective interpolation.

At the next level of sophistication, many different ocean circulation, data assimilation and forecasting models for climate are being developed and used. Most of this work is taking place as part of the climate research programs. No single body oversees or coordinates these modeling activities. Recent reviews (e.g., Weaver and Hughes, 1992; Anderson and Willebrand, 1992; Merlivat and Vézina, 1993; Smith, 1993; Neelin et al., 1992), texts (e.g., Philander, 1990; Bennett, 1992), and reports from associated expert groups (WOCE, 1994a, b; Stockdale et al., 1993) give perspective on the state of the art.

It is not possible to survey the status of each type of modeling here. Briefly, there are now global models for the study of upper ocean nutrient cycling, for carbon uptake and transport, for tropical ocean data assimilation and ENSO forecasting and for a range of ocean circulation and heat and freshwater transport studies. By and large model results are playing a greater role in data interpretation, in experiment design and in blending results and observations into analyzable fields than ever before. Coupled ocean-atmosphere models, with and without sea ice, biogeochemistry and terrestrial processes are also under development and in use for a wide range of purposes. Existing ocean climate model results show substantial inconsistencies with observations.

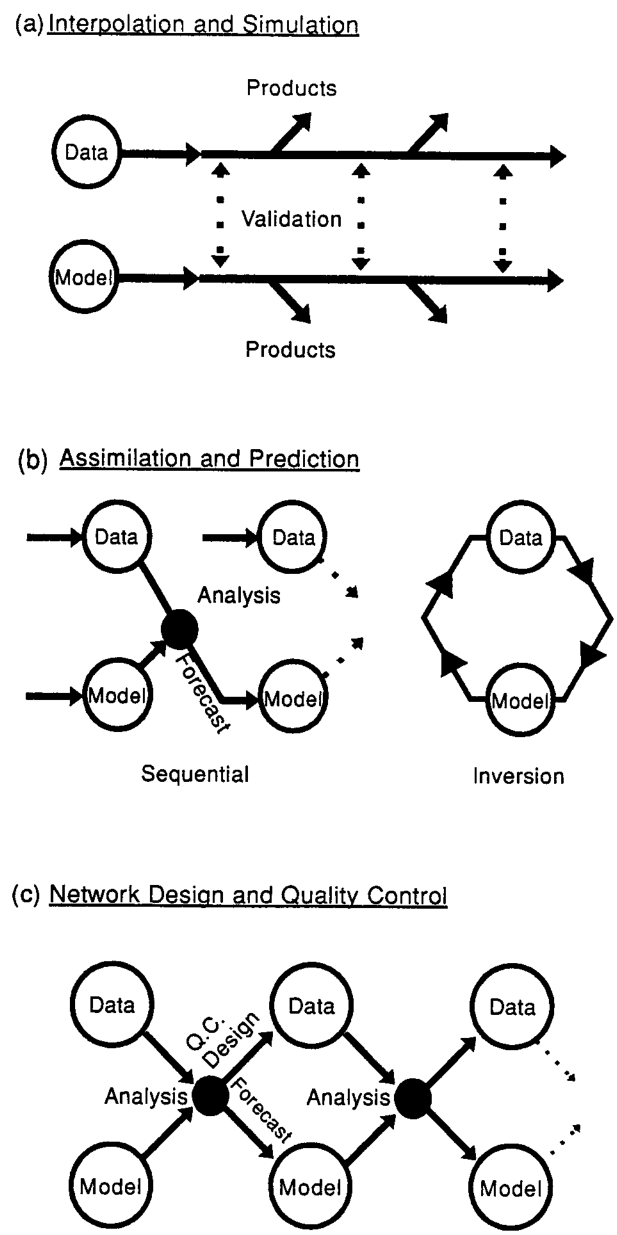



Figure V.J-1. A schematic of three methods for interfacing observations and models, in order of increasing sophistication. a) The data are interpreted without the aid of a model, and the model is run without observed information. The interface is provided by series of validation steps. b) Either the data and model fields are merged in an analysis step, which then provides the basis for a sequential model prediction scheme, or the analysis field is obtained from an equilibrium calculation of the circulation based on observation and model constraints (inversions). c) As for b), but here the analysis also affects the data base—first through quality control and later through modifications to the observation network design based on the joint model-data analysis and forecast (from Smith, 1993).

Exploration of the sources of these discrepancies (e.g., model physics, initial conditions, boundary conditions, model numerical approximations, etc.) and their implications for the use of models in climate research, monitoring and prediction will remain an essential activity for the foreseeable future. The resulting more sophisticated models will serve the observing system in several ways.

Models play many roles in the design of observing systems, as the following simple examples illustrate. 1) Where there is little or no observational information about variability, model results can provide dynamically (or thermodynamically or chemically) consistent results whose statistics and patterns can serve as a guide for observational studies. 2) Model results give perspective on the impact of particular sampling strategies by providing simulated fields which can in turn be subsampled according to the proposed plan, then mapped. These results are then compared with the same quantity evaluated directly from the model. Such methods are sometimes referred to as observing system simulation experiments. 3) Models can help assess the likely impact of uncertainties in initial or boundary conditions on data assimilation or forecast results simply by repeated execution with conditions within the expected uncertainty of these conditions. Such sensitivity studies used to be quite burdensome, but contemporary computing and data storage technology makes these calculations and analyses quite feasible. 4) Models have an important role in quality control of data. NWP has highly sophisticated systems for filtering data sets used in model initialization. Such activity will be needed in the ocean observing system for climate (for further discussion see Section VI.C).

More sophisticated model-data integration involves data assimilation and inversion techniques. These are variants of the linear estimation problem introduced in Section III.D. While the theoretical basis for each is the same, it is common practice to distinguish between combining data and a model in a time sequence (data assimilation) and combining data and dynamical constraints iteratively to estimate a consistent state (inversion). Figure V.J-1 shows schematically the contrasting modes of operation. The common goal is to add value to the data set by extrapolating the local observed information to remote locations in a dynamically consistent way.

A successful model data assimilation or inverse thus imposes a thermodynamical and/or physical consistency on the interpretation of data that could not be obtained simply by objective analysis of the data set. In particular, model forecasts benefit from an initial conditions that is at least partially consistent with the dynamical and physical equations that are used to integrate the model forward in time. Also, in principle, model data assimilation and inversions permit the estimation of related fields that may be difficult, or perhaps impossible, to sample directly.

The techniques of data assimilation are numerous; not every one will be successful in every instance. In fact, some simple assimilations of data into models can yield fields that are not more useful than either the model result without the additional data or an objective mapping of the data. Techniques for assessing the utility of the data assimilation result depend on the use(s) to which the result will be put. Similarly, inverse calculations can be done in a variety of ways and the utility of the result is strongly affected by the choice of constraints and by the method used to determine a particular "optimum" solution. This is because the model systems are typically highly overdetermined by the available data so that there are many equally plausible solutions in the absence of additional constraints (e.g., smoothness requirements).

Both inverse solutions and model data assimilation may be very demanding of resources; this is particularly the case for more advanced techniques like adjoint and Kalman filter techniques (Bennett, 1992). Nevertheless, such techniques offer the potential for extracting greater information and value from the observational system data set. For example, adjoint techniques are being used to assess the sensitivity (predictability) of model forecasts to errors in the initial conditions (e.g., so-called dynamic extended range forecasts) and to model parameterizations. Ultimately, the observing system must balance this added value against the cost of doing such calculations. In all but a few cases it is presently not feasible to use the most advanced techniques routinely but the observing system design must be predicated on the assumption that adequate computational resources will be available in the near future.

Table V.J.1-1 attempts to summarize the present status of models in respect to each of the observational subgoals. This form is by no means precise and the reader is referred to reviews and texts for more detailed assessments. The table indicates that routine application of models in the interpretation of data is not commonplace. However, it also indicates the strong potential in quasi-routine and research developments for the advancement of the observing system; three classifications are offered for models that are candidates for an operational system.

### V.J.2. Model assessment and the observing system

If models are to offer their best in the evolution of the observing system and in climate prediction, it will be necessary to establish a set of model quality assessment procedures for model-data comparisons. Whether used for observing system design, for basic model-data assimilation or for full inverse calculations, the skill of the model has a profound impact on the utility of the results. At present, model assessment is done primarily via rudimentary comparison with either existing statistics, climatologies, or maps. Only rarely have even basic skill statistics like signal to noise ratios or RMS departures from the comparison fields been evaluated for either ocean circulation or coupled model forecasts. Sequential data assimilation skill results have not typically been reported.

The data assimilation and inverse theory framework offers objective assessment opportunities (e.g., Frankignoul, 1991; Bennett, 1992), but these have rarely been explored. These techniques deserve much wider examination and use by both the observational and ocean climate modeling communities.

### RECOMMENDATIONS FOR V.J

The recommendations presented here must be interpreted in the context of the overall goal of the observing system (as represented by goals 1-4 and the various subgoals) and the need to accommodate an advancing and evolving observing system. It is expected that the "research" systems identified in Table V.J.1-1 will move toward a more operational mode as the related observing system elements are implemented; otherwise there is the potential for unnecessary wastage of information.

- J1. Computer and data access resources must be developed throughout the application and research communities to support the improvement of techniques for data interpretation.
- J2. A forum should be established between the research and operational communities to ensure that techniques available for data interpretation and products are maintained at the state-of-the-art.
- J3. Objective assessment of developing and operational models should be included as part of the ocean observing system for climate.
- J4. The use of models in observing system design should be encouraged and supported.
- J5. Appropriate reanalysis of data should be encouraged to ensure high quality data (through objective quality control) and model products.

Table V.J.1-1. Summary of how models are being used to help interpret observations and to fulfill the requirements of goals 1–3. For the first three types, ocean models are directly involved in the data processing (see Figure V.J-1); for the last two types, information is derived principally from boundary conditions and prescribed forcing (e.g., solar or enhanced greenhouse gas). Models that are considered candidates for an operational system are classified with a letter. These classifications are guided by those used for feasibility impact diagrams in VIII. If a type of model is now being used operationally (consistent with our definition in III.C), it is marked "O". If the model application is well tried and tested in research mode, but not yet transitioned to operational, it is marked "R". Finally, if a model remains in research and development for this application it is marked "D". In addition, where a particular model class has been involved in a significant way in the design of the observing network for a subgoal, an asterisk has been added to the table. If there is no relevant activity the table is left blank. The aim is to give a general indication of the level of principal activity and not to simply list the highest/lowest level from all activities.

| Goal Number<br>Short description:<br>MODEL TYPE | 1a<br>SST | 1b<br>wind | 1c<br>Q, E-P | 1d<br>carbon flux | 1e<br>ice | 2a<br>relentless upper ocean monitoring | 2b<br>ENSO analysis/ forecast | 2c<br>global analysis/ forecast | 3a<br>storage | 3b<br>circulation | 3c<br>sea level |
|---|---|---|---|---|---|---|---|---|---|---|---|
| objective/subjective analysis | O * | R * | R | D | O * | R * | O * | | D * | D * | O, R * |
| sequential data assimilation and coupled model initialization | R * | O * | R * | D | | | O, R * | | | | D |
| inversion | | | R * | D * | | D* | | | D * | D | D * |
| ocean simulation | | * | * | D * | D | * | * | D * | D * | D * | * |
| coupled ocean/atmosphere simulation | * | | * | | * | | * | D | D | D | * |

# VI. INFORMATION MANAGEMENT

## VI.A. General Description

### VI.A.1. What is information management?

The various elements of the design for the ocean observing system for climate recommended in Section V will result in vast numbers of in situ and remotely sensed measurements and will generate an equally large suite of processed samples, analyses, and products. For these elements to operate cohesively over the long-term and for each of the stages in processing to proceed in a timely and efficient manner the observing system must incorporate a sound information management strategy, including a workable information exchange policy. For example, Karl et al. (1989) discuss the limitations in the recent climate record due to observational practices, calibration, station changes, data representativeness, data access, and areal coverage. They point out that these problems regarding in situ data together with special issues associated with remotely sensed data (algorithms, short records, etc.) pose challenges for climate analyses. An effective information management system will help to alleviate these problems for future users.

In the present context "information" is defined to include raw and processed data, associated data on measurement methods (metadata), analyzed fields, model output, information on analysis and model methods, and products specifically designed for the user community of the observing system. The "management" includes communications from instruments to responsible centers, quality control, documentation of observing system methods, global communication and exchange of data, data sharing policies, data assembly procedures, regular generation and dissemination of products, and the archiving of information at all stages. "Information Management" is preferred to "Data Management" because it more readily conveys the message that the system must manage all information and not just that directly associated with the geophysical and biogeochemical variables measured by the observing system. This information management must be a part of the overall observing system management. (See Section VII.D for a suggested management structure.)

Within the observing system, information will comprise a diverse range of physical, chemical and biological variables and an equally diverse range of temporal and spatial sampling strategies and coverage. The system will involve communication and processing schedules ranging from near instantaneous (order of a day or less) to a year or more, and will necessitate the development of sophisticated techniques for quality control of the data and product streams. It is also important to recognize that the management of this information cannot be carried out in isolation but must be coordinated with the management practices of weather prediction (i.e., the elements of the WWW program), GCOS (e.g., GCOS, 1993), other modules of GOOS, and plans developed for various research programs.

A GCOS data management plan is currently being developed (the draft version is hereafter referred to as GCOS DMTT, 1994). It describes a comprehensive data management system including procedures for collection, quality control, comparison, dissemination, and utilization of all data relevant to GCOS. This section focuses on the ocean component of that system and highlights those aspects critical for the successful implementation of the scientific design.

The natural basis for the information management strategy is provided by the data and information management plans of the various research programs that provide the basis of the scientific design (TOGA, WOCE, JGOFS). The methods of the WWW, in particular those of the associated marine and oceanographic systems (IGOSS, Global Sea-Level Observing System (GLOSS)), and of the World Data Centers for oceanography (Webster, 1992) also provide valuable guidance. The following sections describe some general principles of the design, the goals of the observing system information management system, existing management systems, data definitions, the primary elements of the system, methods of data acquisition, distribution and quality control, processing operations, distribution of products, and the general requirements for archiving.

### VI.A.2. General principles

While the ocean observing system for climate is a new and exciting oceanographic undertaking there exists a background of experience, principles and international agreements, many developed in support of scientific research, that can be used in developing the information management plan. The following guiding principles have been adopted:

- the information management system will be built as far as is possible and appropriate on existing national and international systems;
- the information management system should be "operational" in the sense defined by Section III.C;
- the information management system should be consistent with the objectives, needs and priorities of the scientific design;
- data should be transmitted from instrument platforms to appropriate data centers and made available for further processing as soon after measurement as is feasible and practical; timely information transmission and exchange is fundamental;
- quality assurance of data and products should receive high priority to maximize the benefit drawn from the often difficult and expensive ocean measurements;
- the information management system should be user-oriented to ensure that the needs of users, the ultimate sponsors of the observing system, are served well;
- full and open sharing of data and information among the participants and users of the observing system is essential to its successful implementation and operation; the proprietary nature of some data collected for scientific research must be recognized and safeguarded, but all such data must be made available to the observing system as soon as possible, reflecting the benefits to the wider community;
- observing system participants should contribute data voluntarily and with minimal delay to data archival centers which in turn should be able to provide information to users effectively free of charge;
- the observing system will be most effective if practical international standards are developed for all phases of information management;
- information management will be most effective if it is part of the overall monitoring and evaluation process of the system; thereby enabling new or improved methods and technology to be implemented for the benefit of its overall function. This implies a flexible and evolving management system.

### VI.A.3. Goals

The general goal for the information management system as set out in Section III.B (subgoal 4b) is: "To provide the data management and communication facilities that are necessary for routine monitoring, analysis and prediction of the ocean state from monthly to long time scales".

In broad terms the aim is to make the flow of information "operational" in the sense defined in Section III.C: the information management system must be built with continuous, long-term operation in mind; it must be systematic in the sense that it is tailored to the elements of the scientific design; it must be relevant by incorporating only those elements that are absolutely necessary, keeping in mind the connections with other operational systems and scientific research; the data flow must be timely to ensure effective utilization of information; it must be cost-effective by focusing on specific needs and priorities, by adopting appropriate technologies and by continual assessment of performance in the context of the overall observing system goals; and finally the management methods must be routine in the sense that they have undergone extensive testing and are well understood and likely to be sustainable over the long term. In a very real sense the information management system for the ocean observing system for climate will require the same experimentation, testing, and fine tuning as did the measurement, analysis, and modeling activities discussed in previous sections. These objectives are expressed in the following goals which must be met by the observing system:

Goal IMS1: To provide for effective data acquisition and communications. This includes:

i) telemetry between instrument sites and responsible data collection centers;
ii) timely communication of data, analyses and products; and
iii) international standards and protocols for acquisition, processing, and distribution.

Goal IMS2: To facilitate assembly, quality control, compositing, and synthesis of data sets. This includes:

i) assembly of data sets for the observing system variables from the various data collection points;
ii) provision of effective quality control to the data;
iii) composited and compressed data sets from the various types of measurements for easier utilization and processing; and
iv) performing data rescue as appropriate.

Goal IMS3: To promote the establishment of a distributed system of application centers for the creation of value-added products as required by users.

Goal IMS4: To establish a robust and accessible system for gathering, storing, distributing, and preserving information. This includes:

i) the implementation of a data base and permanent archive for observing system data, analyses, and products;
ii) maintaining a data base with information on measurement and processing methods and on calibration and validation; and
iii) the creation of a Data Information Unit (DIU) for the provision of details on the information management system itself.

Goal IMS5: To provide effective management and a workable information exchange policy. This includes:

i) management of the information management system and its interactions with other climate, weather, and ocean systems; and
ii) implementation of an international agreement on the free exchange of information.

A strategy for fulfilling these goals is developed in the remainder of Section VI.

## VI.B. Foundations of the Information Management System

### VI.B.1. Existing operational systems for information management

Annex II, "Linkages to Existing Systems", gives background to WWW, IGOSS, GLOSS, and the International Oceanographic Data and Information Exchange (IODE), four systems which will provide part of the foundation for the Information Management System for the ocean observing system for climate. Previous sections have given some background on related scientific programs. The GCOS Draft Plan (GCOS, 1993), Webster (1990, 1992), and Wilson (1992) provide additional background. This section discusses some implications for the development of the present plan.

Meteorology. The GTS and the Global Data Processing System of WWW provide the core of the information management system for operational meteorology. The GTS comprises a network of telecommunication services for the rapid exchange and distribution of observational data and processed information. The principal goal of the GTS is to ensure observations are provided in a timely manner (within hours of measurement; so-called real-time) to all the national meteorological services in order that they may proceed with regular (once or twice daily) regional and/or global forecasts.

The GTS nodes are usually located in national centers so that a variety of other telemetry and communication systems, as well as low-level processing and quality control, may be involved between the instrument and the GTS. The data are collected as part of the Global Observing System of WWW; there exist a variety of WMO manuals, regulations and guides to cover the operations of the observing system, the GTS and processing. A similar strategy will be needed for the observing system. Of fundamental importance to the operation of WWW is an agreement that in essence assures the free exchange of all information among member nations thus allowing smaller nations access to global data sets while at the same time enabling global coverage through active participation of all nations in taking observations.

Data collection and communications are not homogenous over the globe. The vast amounts of data from satellites and from complex, high resolution models has outstripped the capacity of the GTS in recent times and the Commission for Basic Systems of the WMO, the body with oversight responsibility for WWW, has been seeking and testing new technology for more rapid and convenient exchange of information. Management support is the responsibility of the WWW Data Management facility which coordinates, manages, and monitors the flow of information within WWW in accordance with international standards and practices. The archiving of data is the responsibility of a network of World Data Centers for meteorology.

The WWW will be at least partially responsible for the data and products which enable the determination of surface fluxes and surface fields, an important component of observing system data management (see Sections V.A, V.B, and V.C). It is important that common elements of the WWW and the observing system information management system are integrated, perhaps through joint participation.

Operational Oceanography. IGOSS was established in 1967 jointly by IOC and WMO as the marine and oceanographic counterpart to WWW, albeit on a much reduced scale. Since that time IGOSS has been the focus of all real-time oceanographic information exchange and has taken a role in the data management activities of various research programs such as TOGA and WOCE.

In the sense that IGOSS was created as an oceanographic equivalent of WWW, it is in many ways an early manifestation of GOOS. However, there were no scientific design or long-term goals for IGOSS. Instead it operates as an entity encompassing oceanographic activities and client needs as they arise. One of its key contributions has been to provide a real-time facility for oceanographic research, particularly for TOGA. The facilities for real-time communication, coordination and international cooperation in oceanography have developed and matured within IGOSS in parallel with the development in scientific understanding and knowledge under TOGA and more recently WOCE.

IGOSS provides experience and expertise that will be valuable for information management within GOOS. However, because of its multi-faceted role, it is not immediately clear what role IGOSS will play with respect to GOOS. If we use the WWW as our model, so that GOOS is in essence the oceanographic equivalent of the WWW Program, with climate as one of its modules, then IGOSS might assume the more specific task of oversight of communications and information distribution. (The use of the WWW as an analog for GOOS, while convenient, should not be interpreted too literally. The oceanographic equivalent to NWP is short-range predictions of eddies and fronts at roughly weekly time scales. The combined activities of WWW, the Global Atmospheric Watch, and the World Climate Program (and its operational activities via GCOS) are probably the more appropriate analog. There is also a vast difference in maturity between meteorological and oceanographic systems.) Wilson (1992) provides a somewhat different model with IGOSS and IODE combining to form a "Data Management and Communications Entity". These matters need to be discussed by the broader communities of WWW, GCOS, and GOOS.

GLOSS is a unique entity because a) it is concerned with a very specific observational domain; namely, sea-level, b) it is quasi-operational in the sense that it is a systematic, routine system for sea-level observation with long-term objectives, c) it effectively oversees its own communications and data archiving, and d) it has links with research programs such as TOGA and WOCE, and with climate change research in general. GLOSS has developed data management practices, partly in association with IGOSS, for its clients. It is not clear whether GLOSS should continue as a separate entity and, as a specialized technical/scientific group, provide advice to GOOS scientific and implementation groups. It is clear that the majority of the tide gauges of the existing GLOSS network are not useful to the ocean observing system for climate defined by this report.

IODE is responsible for coordinating international exchange and archiving of oceanographic data including establishment of codes and standards. Its development has been driven largely by the research community. Indeed, the World Data Centers for Oceanography, which provide the backbone of the IODE, were originally created for research and are still governed by the scientific community through ICSU (Webster, 1992). Through its close relationships with programs like TOGA and WOCE, the IODE has been evolving into a system that can accommodate the needs of climate research. This association and development means the IODE is already partly attuned to the observing system needs, though the needs of an operational system and the associated increase in volumes of information will require further adaptations and development. Two aspects that require development are methods for integrating metadata and quality control information into data bases and methods for handling all but the most conventional data.

One of the guiding principles of IODE has been that all concerned should contribute voluntarily to the data centers for their mutual benefit. Users of the IODE system are able to access data freely (though perhaps subject to some scientific proprietary conditions) at minimal cost. It is a principle needed for the observing system to ensure that all partners and the scientific community have access to all data.

The GTSPP is an initiative of IGOSS and IODE aimed at modernizing oceanographic data management practices and techniques. In part it grew from a recognition that oceanography required developments in information management that kept pace with those of science. A detailed background is given in Searle (1992). The initial focus has been on producing high quality temperature and salinity data sets for both real-time and delayed mode use and on improving the standards of data exchange. A unique aspect of this project has been the strong involvement of the scientific community. As an example, the GTSPP and the WOCE Upper Ocean Thermal Data Assembly Centers have cooperated in the distribution and quality control of temperature data collected through TOGA, WOCE, and various other measurement systems. This has resulted in many advances in the standards of data representation and exchange and, in particular, in the methods of scientific quality control of thermal data. The GTSPP is perhaps a paradigm for what is needed for all the elements of the observing system, not just subsurface temperature and salinity observations.

### VI.B.2. Data management in ocean climate research programs

TOGA. TOGA information management was built largely on existing systems (recalling that a significant part of TOGA involved meteorological data and analysis) with emphasis on real-time collection and transmission of data (ITPO, 1990). Because TOGA has as one of its goals the prediction of interannual climate variability using models initialized with ocean data, it is important that oceanographic data be collected and distributed as rapidly as possible, with minimal loss of information or introduction of errors in transmission, and with agreed standards for quality and transmission of information. TOGA relied on IGOSS for real-time transmission and various World Data Centers for archiving and further dissemination of data and products.

The emphasis on real-time collection and distribution of all ocean data led to many changes and improvements in the way oceanographic data are handled by the GTS—including changes in the format of BATHY and DRIBU/BUOY/DRIFTER messages, allowance for quality flags, allowance for information concerning instrumentation, and accommodation of data from fixed moorings like TAO. Telemetry has evolved from a system which mainly used manual encoding and transmission via ground stations to one in which data are automatically collected, encoded, and transmitted using satellite systems. Early unreliable data transmissions during TOGA (faulty messages and poor reception rates) have gradually been overcome, driven in part by the greater importance now attached to such data. Ocean drifter data (position, SST, etc.) are also regularly distributed in real-time.

Scientific research in TOGA has been dependent on a reliable system for ocean data archiving and dissemination, and an active program of data rescue. TOGA has provided several new initiatives in methods and technology. A Pilot Project in the use of CD-ROMs for dissemination of data and analysis products was initiated and has met with significant success; the TOGA Subsurface Data Center, lately in association with the GTSPP and WOCE Upper Ocean Thermal Data Assembly Centers (DACs), has developed improved methods for exchange of data, data cataloguing, maintenance of distributed data bases, and modern approaches to information dissemination.

TOGA does not have a formal data sharing policy because free and wide sharing is effectively assured by the principle of rapid transmission and exchange of data by TOGA scientists and by involved national analysis and data archive centers.

WOCE. Data management in WOCE is outlined in WCRP (1988a). In contrast to TOGA, the emphasis of WOCE data management is less on real-time exchange and data for model initialization and more on assembling high quality, comprehensive, unified ocean data sets useful for developing and verifying models of the global ocean circulation. This is to be achieved through a decentralized system of data assembly and special analysis centers at research institutions and national data centers with direct participation by WOCE scientists, supported by a DIU, and the World Data Centers (WDC) and IODE for archiving and delayed-mode information exchange.

The decision to build a distributed system with the DIU providing connectivity is a sensible one in view of the volume of information, the lack of experience in handling some of the new types of data (e.g., floats and ADCPs), and the emphasis on quality. WOCE is also relying on satellite data, particularly altimetry, and so new methods and technology must be developed to enable information to be available to the users (analysts and modelers). At this early stage it is already clear that the DIU has been an extremely successful concept. Similar units are being used in TOGA COARE and for the Earth Observation System.

The cooperation of the Upper Ocean Thermal DAC with GTSPP is having a positive impact on data management for ocean temperature. In particular the methods and standards of quality control have advanced considerably (WOCE, 1993) as have the standards and formats for exchange of such data. The observing system strategy must be to encourage the development of data management methods within research programs like WOCE with a long-term view toward the time when these experimental information management practices can become routine.

WOCE has experimented with a data sharing policy which tries to balance the proprietary rights of individual data originators with the fundamental need for data sharing (WCRP, 1988a; WOCE, 1994c; Webster, 1990). A similar policy might be required in the observing system to safeguard the rights of scientists if research data are to be made available and incorporated into the system data stream. It is too early to tell whether WOCE has achieved the correct balance, though there are some indications that the flow of data into data centers is lagging (WOCE, 1994c).

JGOFS. The data management tasks of JGOFS (Flierl et al., 1992; Webster, 1990) are particularly interesting in that there is almost no previous experience in archiving and exchanging biogeochemical data. JGOFS, while global in name, is in essence a series of regional experiments and the data management plan directly reflects this loosely connected approach. The data management system consists of a group of loosely interacting national centers; scientists will provide data to their national center which will in turn ensure their data holdings are exchanged with all other JGOFS data centers. The analysis of biogeochemical data is still far from routine and usually demands considerable scientific effort. The methods are still undergoing testing and development so that uniformity in quality and products is not yet assured.

JGOFS has explicitly recognized the value of allowing unrestricted reading access to their data base. This policy was adopted in the belief that free and open exchange of information is essential for improvements and optimum growth in the science and for the ongoing design of JGOFS experiments. It also implicitly recognizes that the program is funded at public expense and must therefore be willing to allow wide use of its data. JGOFS places the onus on individual scientists to honor the rights of data originators.

### VI.B.3. Data definitions

Level I data are instrument readings, often in engineering units, that are used to infer meteorological and oceanographic variables. In recent times (e.g., in WOCE), a further level (Level 0) has often been invoked to distinguish raw signals which are only indirectly related to the geophysical variable (e.g., a satellite measures a radiance in space (Level 0 data) which is turned into a surface radiance though empirical relationships (Level I) which in turn is used to infer SST (Level II)). This distinction will not be made here. Level I data will normally be managed at the source (by the originator or originating agency or institution), although information on the technology should be available through the DIU. In some cases where reanalysis (from Level I to II) may be warranted, perhaps because of significant improvements in algorithms, a more formal archive may be warranted (refer to Section VI.C.4).

Level II data consist of values of the universal meteorological and oceanographic variables either obtained directly from instruments (e.g., a thermometer measurement of SST) or indirectly from Level I (e.g., SST from AVHRR). It is usual to distinguish two sub-classes of Level II data:

- Level II-a data are those exchanged without significant levels of quality control and usually in near-real-time (say, less than one month after measurement); they are used in NWP and for monitoring, detection and predictions on monthly to interannual time scales.
- Level II-b data are those that have been gathered after some delay and/or have been subjected to a significant level of quality control.

The distinction between Levels II-a and II-b has become blurred for ocean climate applications. Real-time data are usually subject to objective, and sometimes subjective quality control prior to analysis; in many instances this is the only feasible means for screening data. On the other hand, delayed-mode data bases often contain real-time data as the original record is not available. So a data base may be stratified in many different ways, not just according to the definitions of Levels II-a and II-b. For the ocean observing system for climate, emphasis will be on assuring that all Level II data have a complete history attached, detailing instrumentation, transmission, processing and quality control.

It may also be convenient to consider a third sub-class which recognizes the fact that analysis centers may not always be able to deal with the volume and complexity of the Level II-a and II-b data sets.

- Level II-c are data summaries for which the complex temporal, spatial and parameter span of the original Level II data set has been compressed (summarized) into a more convenient form but without significant recourse to extrapolation, interpolation or inference. The COADS data summaries (Woodruff et al., 1987) are an example. Such data summaries are different from analyses, for example Levitus (1982), where significant assumptions have been made in order to present the information on a regular grid.

Level III data are products derived from analysis of Level II data, usually in the form of regularly gridded fields ideally with associated error estimates. The processing involves significant levels of re-interpretation, interpolation and inference, often through model data assimilation. Model analyses and forecasts are examples of Level III data. Because analyses are sometimes distributed directly to the user community (e.g., SST maps), it is sometimes more appropriate to refer to Level III data as products (here a product is viewed as the final outcome of a processing chain). Scientists constitute a large user group for Level III products. On the other hand, there are many users who will not want Level III data and will seek further processing with perhaps added value; this suggests a further level definition.

Level IV data consist of products derived after further processing and consolidation of Level III data. This may take the form of a regional re-interpretation or perhaps the incorporation of independent information. A seasonal climate outlook based (perhaps subjectively) on the Southern Oscillation Index, SST and subsurface ocean analyses is one example. Global sea level or SST records for long-term climate change (e.g., Barnett, 1984; Folland et al., 1990) provide other examples.

## VI.C. Elements of the Information Management System

The information management system can be broken down into distinct, but connected, elements, much as has been done for the observational elements (Section V). Usually these elements directly address one of the goals ISM1 through ISM5 or some part of those goals. The following sections discuss these elements in detail.

### VI.C.1. Data acquisition and communication

The existing system. Existing methods have evolved in the service of NWP and as a result of experimentation in research programs. For in situ marine data a mixture of manual and automated methods is used to communicate observations routinely collected by VOS and autonomous platforms through national meteorological centers and hence onto the GTS (Annex II). Oceanographers have increasingly used satellites as the link from platform to data dissemination points. The GTS, plus some informal links between national centers, provides the means for distributing the data globally. The management of these communications has been the responsibility of WWW and it is to be expected that it will remain so, but perhaps with more explicit participation by GOOS and GCOS. This is necessary to ensure that the system functions effectively for the ultimate benefit of the observing system, something that is not guaranteed when the only consideration is NWP. The VSOP-NA and other experience discussed in Sections IV and V suggest that particular attention needs to be paid to the documentation of instrumentation and the quality of data. There is also a need to ensure that all marine data are made available to, and whenever possible used by, analysis systems.

Satellite data enter the system by a variety of means depending upon the originator. For example, data from AVHRR flown on the NOAA series of polar orbiting satellites are processed by the National Environmental Satellite, Data and Information Service (NESDIS), beginning with the raw sensor radiances (Level Ib) and using various cloud and land detection schemes with a multi-channel SST algorithm (McClain et al., 1985) to obtain Level II SST data. A subset of the latter data are put on the GTS. Some ERS-1 data are also routinely available in real-time, again relying on a specialized, dedicated center for processing the raw data into useful information on the natural variables (e.g., surface wind stress and sea state).

Management of the real-time ocean data flow is the responsibility of IGOSS. Although this overall system has been satisfactory for most purposes, it is limited by low data rates, inflexibility in transmission formats, and unreliability of the communications. It is also restricted because of the lack of two-way communication with instruments. The cost of collecting data makes it extremely important that these deficiencies be addressed. The need to upgrade all technical means of transmitting the data from the sensor to the ultimate user is paramount.

The observing system must make it a priority to get data quickly into the responsible centers for quality control, preliminary analysis and archiving. Experience suggests any delays severely compound the problems of information management.

The system for distribution of Level III and IV data (analyses and products) is largely ad hoc. The surface analyses derived from NWP systems are mostly available in delayed-mode, usually through the activities of research programs (though such analyses are often used locally in near-real-time for oceanographic applications such as wave models). In some cases, analyses are available through informal Internet arrangements. For example, the SST analyses produced at CAC are available both through the Internet and via the GTS. Various centers distribute hard copy of analyses and products derived from oceanographic data (e.g., the CAC Climate Diagnostics Bulletin; the JMA El Niño Monitoring Centre Monthly Ocean Report; the IGOSS Products Bulletin). For research purposes, the CD-ROM has proved a popular medium for both observation and analysis distribution.

Observing system telemetry. In the past, oceanography relied on dedicated vessels to provide in situ sampling. The results were stored and relayed back to the laboratory by the ship. The cost of ship time prevented long station occupations or simultaneous measurements at several sites. Surface and subsurface moorings provided an alternative strategy whereby instruments could collect information from several locations simultaneously while remaining on site and the data could be collected at some convenient later time. The cost of moorings with their instrumentation and of the ship time to service them results in a cost per data cycle which is relatively inexpensive compared with that of taking measurements repeatedly from a vessel under way or at oceanographic stations. Improved mooring technology and sensor durability and stability, has encouraged scientists to plan projects with longer recording times (up to two years) and thus encouraged longer deployments. The down side is that there are long delays between measurement and data acquisition, and occasionally, the data are lost through mooring failure.

Telemetry of data from instrument platforms overcomes these problems by immediately communicating information to the collection site (Briscoe and Frye, 1987; Frye et al., 1991; Dickey et al., 1992; Soniera, 1994). Such technology is essential if the observing system is to meet its goals of timely collection and dissemination of information (but note that these goals differ for different observing system data sets). Real-time telemetry has been employed with the VOS XBT program, TAO, surface drifters, and subsurface floats, but the low data rates and lack of an instrument command link pose severe limitations. Using a single transmitter and Argos allows for the transmission of only about 3 Kbytes per day (Dickey et al., 1992).

Tables VI.C.1-1 from Frye et al. (1991) and VI.C.1-2 from Soniera (1994) attempt to summarize the possible trade-offs between effective data rate and cost. Brooks and Briscoe (1991) point out the important distinction between a peak, instantaneous data rate (e.g., about 256 bits per second using Argos) and that which can be sustained over long periods allowing for the limited time-

TABLE VI.C.1-1 Telemetry Tradeoffs for Oceanographic Measurements from Offshore Buoys (from Frye et al. 1991)

| Telemetry option | Coverage | Typical throughput | Power Requirement | Platform Location | Hardware | Costs Per Month | Per bit | Long-term availability | Receive Station |
|---|---|---|---|---|---|---|---|---|---|
| ARGOS | Worldwide | 0.02-0.2 bps | 1-10 J/bit | ± 1 km | $2k | $236 [bc] | $0.0004 | Yes | Not required, but available ($40k) with limited coverage |
| ATS | Hawaii to Azores but non-polar | 0.3-1.2 kbps | 0.5-1 J/bit | N/A | $6k | 0 | 0 | No | Not required, but available ($5k) |
| GOES/METEOSAT/ GMS/INSAT | Worldwide except polar regions | 0.2-2 bps | 1-2 J/bit | N/A | $3k | 0 | 0 [c] | Yes | Not required, but available ($40k) |
| VHF (Line-of-sight) | 10-50 km from receive station | 0.3-1.2 kbps | 0.02-0.1 J/bit | N/A | $1-2k | 0 | 0 | Yes | Required ($5k) |
| Meteor burst | 2000 km from master station | 1-20 bps | 0.2-1 J/bit | N/A | $5-10k | 0 | 0 | Uncertain | Required ($100k) |
| HF packet | Variable, up to worldwide [d] | 1-30 bps | 1-10 J/bit | N/A | $2k | 0 | 0 | Yes | Required ($10k); may need several |
| RECENT [f] | | | | | | | | | |
| Inmarsat Standard-C | Worldwide except polar regions | 10-100 bps [g] | 0.5-1 J/bit | N/A | $5-10k | 0 | 0.00125 [g] | Yes | Not required |
| Geostar | Coastal US | 0.1-10 bps [g] | 0.01-0.1 J/bit [h] | ±7 m | $3k | $45 | 0.00016 | Not known | Not required |

NOTES:
(a) Not continuously-orbiting satellite
(b) Basic charges are monthly: per bit charges are based on assumed data throughout. Many users get large (to 100%) discounts.
(c) Extra costs are required to obtain data via telephone or tape.
(d) Lower data rates, more power required at longer ranges.
(e) More receive states increases efficiency.
(f) Systems existing as of 1988.
(g) Estimates.
(h) Spread-spectrum technology, hence low power requirement.

| | Type | Analog/ Digital | Size of Antenna dia. & ht. | Size of Terminal | Weight of Terminal/ Antenna | Cost per minute |
|---|---|---|---|---|---|---|
| **Inmarsat A** | voice/telex fax | analog | 0.9-1.2 m (3-4 ft) | various size of computer/ phone/fax | 120 kg (264 lbs) | \$6-\$8 voice \$4 telex |
| **Inmarsat B** | voice/telex fax | digital | 0.9 m (3 ft) | various size of computer/ phone/fax | 100 kg (220 lbs) | \$5-\$6 voice \$3-\$4 telex |
| **Inmarsat C** | telex/data | digial | 0.3 m (1 ft) | various size of computer/ phone/fax | 10 kg (22 lbs) | \$1 - \$1.50 telex |
| **Inmarsat M** | voice/fax | digital | 0.5 m (1.7 ft) | various size of computer/ phone/fax | 25 kg (55 lbs) | \$3-\$6 |
| **Inmarsat P** | voice/data | digital | n/a | handheld | 750 grams (2 lbs) | not yet determined |
| **Iridium** planned | voice/data fax, paging | digital | n/a | handheld | handheld | \$3 + \$50/month |
| **ORBCOMM** planned | data/fax | digital | n/a | handheld | handheld | \$.50 1st 250 char. \$.004 per char. thereafter |
| **Globalstar** planned geolocation | voice/data fax, paging | digital | n/a | handheld | handheld | \$.30 |

Table VI.C.1-2. Specifications of most current and planned satellite communications services available to the mariner (from Soneira, 1994).

window in which data can be transmitted (e.g., about 1.5 hours per day for Argos) and the need for some transmission redundancy. The cost estimates in the Tables are not total system cost, but just the cost of the telemetry link. For many of the applications of concern to this observing system, Argos has been the dominant form of telemetry in the recent past because of its wide availability, the ability to do position fixing and telemetry simultaneously, and the possibility of direct access into the GTS.

Problems of cost have been mitigated to some extent by the Argos Joint Tariff Agreement with WMO and IOC. Geosynchronous systems offer a more attractive data rate but require a ground station with relatively high power needs and/or directional antennas on the ground platform or the satellite. For platforms on land or ships, geostationary satellites—INMARSAT and the GOES-class satellites—are used.

The existing systems such as Argos and GOES will satisfy part of the requirements of the observing system platforms, such as drifters and some of the VOS fleet, though it is essential that telemetry costs be reduced further. There are however two factors which indicate the observing system must search for improved telemetry. 1) The low effective bandwidth of present systems is not acceptable in the long-term. For networks such as TAO and the VOS XBT lines these limitations place severe restrictions on the information that can be conveyed in real-time. For some climate applications this loss of information is not tolerable. In most cases real-time data are replaced in the data base by the in situ recordings at some later time, but it seems clear that a more effective system would make more of the original data available in real-time. For surface moorings, in particular those with many sensors, the low data rate places limitations on the temporal sampling and on the total information that can be transmitted, a particularly severe limitation for biogeochemical sampling (Dickey et al., 1992). This is also a problem for floats and other pop-up devices which ideally would like to down-load all stored information. 2) At present the sampling rate and general operation of platforms is fixed at deployment and cannot be altered until the platform is serviced or recovered. It is also not possible to interrogate the state of a system remotely. While the instrument hardware generally exists there are at present few options available for two-way communications. Such flexibility is highly desirable for expensive monitoring sites and for deployments such as TAO.

Dickey et al. (1992), Brooks and Briscoe (1991), Frye et al. (1991), and Weller and Dickey (1992) discuss some promising solutions. There are several satellite systems which could increase the data rate by several orders of magnitude but, at this time, these systems are either not assured or still require considerable development. Satellite-based cellular telephone systems coupled with GPS for positioning would certainly redress both the deficiencies discussed above. Brooks and Briscoe (1991) discuss an interesting alternative which uses direct high-frequency ionospheric radio propagation though, as the authors point out, the irregularity of transmissions and the possibilities of interference and delays are significant disadvantages.

<u>Communications.</u> It is self-evident that the goals of the observing system can only be met if an effective system of communication from instrument platforms to data assembly centers, to analysis centers, to archive centers, and finally to users is maintained. It is fortunate that communications have been developing rapidly in recent years to the point where it is feasible to use products based on measurements taken just hours before. The circulation of information at all levels (other than observing site to collection center), from primary data through products, is discussed here. The communication system must accept information from and deliver information to locations throughout the world. It is imperative to ensure that the communication system allow maximum benefit to be drawn from the observing and processing elements.

It is important that the communication system provide both broadcast (store and forward) and interactive (request-reply) capabilities (GCOS DMTT, 1994). The broadcast method is suited to real-time and near-real-time applications where the various collection and analysis centers put data into circulation, read and store data already in circulation, and ensure information received is forwarded as necessary to other possible users. This ensures rapid dissemination and global circulation of information. The request-reply method is more applicable to non-real-time applications where users are pro-active and request certain information to fulfill particular requirements (e.g., an assessment of sea-level rise). The observing system can be expected to need both methods: store and forward capabilities for the determination of surface fields and fluxes and for monthly to interannual climate description and forecasts; and interactive capabilities to access delayed-mode data sets and archives for climate assessments.

The GTS currently provides communications for operational meteorology and oceanography. By modern standards the GTS has a relatively low bandwidth but it does provide access to and from most countries of the world and is secure. For the observing system and for climate applications in general it is important that information degradation (both data loss and transmission errors) be minimized. This has proved a difficult task for the GTS as diverse data types are added and larger information rates are demanded. Current experience suggests the GTS is capable of providing an adequate service for most real-time and near-real-time applications though this same experience has shown that more modern methods should be explored.

The Internet is an informally connected system of regional, national and international communication networks established initially as a means for exchange between research institutions. The use of Internet has grown to the extent that it now supports many millions of participants through a range of governmental, commercial and research institutions, through all of the developed countries and an increasing proportion of the developing countries. The Internet has provided a de-facto standard of information exchange protocols (e.g., electronic mail and ftp (file transfer protocol)) and has been an essential element in several recent research programs (e.g., TOGA COARE). It has many attributes which make it well suited to the "distributed data base" concept (Section VI.C.4). The use of Internet as a communication system for the observing system (and GOOS and GCOS) will depend on, among other things, its availability through the majority of the participating nations and solutions to the perceived lack of security and guaranteed access. GCOS/GOOS would need to share the Internet with many other users whose demands could not be predicted or overridden and this could compromise the ability of the communication system to deliver reliable and timely service.

The Commission for Basic Systems of WMO is actively seeking a more modern GTS with Internet-like features. Such a system would exploit new technology and exchange protocols so that the band-width of day-to-day information exchange would be greatly increased. Such a system might be run along side the conventional GTS until all nations were able to participate and, with suitable gateways to the GTS and public communication networks like Internet, could provide a flexible, high-capacity element for the observing system communications.

Information flow in the observing system will also be achieved through a variety of other methods including mailed media (cartridges, CD-ROMs, etc.), facsimile, dial-up connections, dedicated networks (e.g., the CEOS network, ScienceNet) and satellites (e.g., down-loading satellite information at many different ground stations). The GCOS DMTT (1994) discusses some of these data flow mechanisms.

Ultimately cost, effectiveness and benefits must all be considered in developing the appropriate observing system communication system. In some cases timeliness is the ultimate consideration and some loss of information can be tolerated; in other cases delays of several days may be tolerable in order to increase the net information content and quality; in yet other cases timeliness may be of little or no concern but it may be critical to ensure both the quality and quantity of information is optimal. The challenge is to provide a system that can effectively and efficiently meet these different needs.

A point that should be re-emphasized is that delays in data delivery compound all other problems of data management. Contributors to the observing system should expect, as part of the "operational" requirements, a strict time delivery schedule.

### VI.C.2. Standards, protocols, and formats

Two important characteristics of the observing system are its dependence on global observation networks (no part of the ocean is irrelevant) and global cooperation in the collection, distribution, and analysis of this information. Recognizing that these are likely to be managed by the participating nations, within which there are likely several cooperating agencies and institutions, immediately emphasizes the need for agreed standards for communication (protocols), for information exchange (formats), for data base management (both on how to gather information on data base content and how to extract data) and for permanent archives (how and what to store, and for how long). The usefulness and effectiveness of interaction between the different elements of the observing system ultimately depends upon the ability to exchange information without loss of fidelity, with optimum efficiency (protocols and formats suited to the task at hand), and with reliability (the client and server have full and mutual understanding of the information being exchanged).

Telemetry and communications. For the most part, industries and operational and research establishments providing such facilities have reasonably well developed standards and protocols. For example, the ftp popularly used with Internet has provided effective exchange of textual and binary data for many years. This is not to say that ftp is suited to all the needs of the observing system and, in particular, to providing the necessary client-server protocols for complex oceanographic data bases, but it is a well established and widely recognized protocol albeit a de facto standard. It may be reasonable to assume that the telemetry and communications industry can provide, or will provide on demonstration of "demand", standards and protocols capable of meeting the observing system needs.

Information exchange. The pros and cons of carrying a large overhead in standardized formats and codes are well known. Within the ocean observing system for climate and GOOS in general, there are going to be two extremes of data sets. At one end of the spectrum, the most highly-developed and mature data sets will be measured almost completely automatically, and transmitted in real time with minimum human intervention. At the other end of the spectrum, there will be experimental data sets with a large number of novel variables measured by novel sensors, requiring unconventional data formats and a great deal of quality control and processing before the data can be released into the public domain. For the real-time and near-real-time data streams there must be some fixed standards and protocols, together with security precautions to prevent contamination or corruption of the data before they are assimilated into models. It must be impossible for unchecked non-standard data sets to contaminate the fast standard data stream. This will incur some overheads, but the alternative of treating every data set as a special case on its merits is totally unacceptable. There has to be standardization of the data streams which have become mature, and where the scientific community has agreed and accepted the routine procedures of calibration, data quality checking, etc. One would expect new and experimental data types to progress gradually over a decade or more from the experimental research status through to standardized and automated procedures and formats.

The WMO has devoted considerable effort to standards for exchange of operational meteorological data and, through IGOSS, for real-time oceanographic data. The WMO Codes and Formats manual provides a detailed and precise description for the method of encoding and decoding information exchanged via the GTS and between national centers (e.g., the BATHY message format for exchange of ocean temperature profiles as text). While this system has proven very effective, its complexity and comprehensiveness does place a considerable burden on participating nations because software must be maintained to cope with changes in hardware and formats. Thus, changes must be kept to a minimum, reducing flexibility. Advances have been made toward more flexible formats (e.g., BUFR and GRIB for binary exchange of observations and gridded fields). There is interest in the use of BUFR as the general code for distribution of ocean data; through its use the observing system could be compatible with WWW and IODE data exchanges. However, considerable development is still needed to enable the full exchange of information likely to be generated by the observing system (particularly non-physical data).

It is daunting to contemplate generalizing codes and formats to cover all oceanographic data and the exchange of non-real-time information, where greater emphasis is placed on the net information content and quality. The IGOSS strategy has been to develop standards and formats for each variable and/or data type as the need arises. There are few information exchange standards which are applicable outside the limited focus of their own communities, and meteorology and oceanography data exchange is no exception. Such a strategy necessarily devotes a considerable proportion of the information management effort to standards and formats. It may be timely for GCOS and GOOS to explore more general standards for information exchange, preferably that have some support outside the community, so that some of the pressures of maintaining an "industry" standard might be alleviated and more use made of "off-the-shelf" software and hardware.

Standards for the format of exchanged data must also be agreed upon. For example, as part of the GTSPP, a format for storage of oceanographic data has been developed (the so-called GTSPP format has both binary and character forms and has been used to store, among other things, drifter data and temperature and salinity profiles). Participants in the WOCE Upper Ocean Thermal DAC, as well as several research and operational agencies, have used this format to exchange data among participants, the generality of the format permitting exchange of detailed information and data processing history. It is important that such formats are developed for the full suite of observing system data and that all participants have ready access to software to read these formats, or to translate data between different formats.

Data base management. It is impractical to suppose that any one data base system will be used throughout the observing system. Yet the concept of a distributed system of data gatherers and data holders requires that all users of the observing system must be able to interrogate a variety of data bases to ascertain where relevant information is being held and, having obtained this information, be able to extract the data efficiently in a format that the user can understand. Information on data bases and data holdings will for the most part be the responsibility of the Data Information Unit (Section VI.C.4) but this unit will usually provide only the directory to the data. Having found the pathway the user will need to access the data base itself to read the "headlines" of data sets (e.g., spatial and temporal descriptors; variables; metadata; processing information). For the observing system, an important initial information management task will be to agree on a minimum set of descriptors for data sets (GCOS DMTT, 1994).

Archives. It is important that the standards for temporary and permanent storage of data be uniform. It should be clear to all holders of data (from Level I through to Level IV) what their responsibilities are in regard to their data holding. Clear standards must be developed outlining when data is considered to be of enduring value and must therefore be kept indefinitely. Standards might also need to be developed for the storage media (the lifetime, access times, etc.). The existing oceanographic data centers are for the most part well aware of such considerations. For the observing system, particularly in view of its proposed dependence on distributed data centers, it will be important that the various national centers are well acquainted with these standards and are able to freely exchange data amongst themselves.

### VI.C.3. Data assembly and quality control

Data assembly. In general terms this is the process of turning Level I data into Level IIb or Level IIc data. In other words, it is not simply a matter of turning instrument readings into measurements of variables, but involves adding value through such actions as quality control, organization (duplicate checking, sorting, formatting), and congregation and consolidation of information. In some cases, such as the use of NWP centers to produce surface fields and surface flux analyses, data assembly is just one part of an automated and complex data analysis, assimilation and model forecast system. In other cases, such as monitoring and predicting ENSO, there is sufficient time during ocean data assembly for some rudimentary screening of data (the GTSPP is an example). For problems where information is limited, such as observing long-term climate change, data assembly may be a critical stage in the process of going from observation to products. For example, monitoring the carbon cycle will require expert attention to complex biogeochemical measurements. Similarly, detecting signals related to greenhouse warming in ocean data will require specialist attention to the quality and the representativeness of the data (e.g., Karl et al., 1994). In general, it is expected that specialized data assembly centers will be an important element of the ocean observing system for climate.

The meteorological analogies to data assembly centers are those centers dedicated to transferring satellite information into Level II data (e.g., NESDIS for remotely sensed temperature soundings; ESA for scatterometer surface winds; JMA for cloud drift vectors) and the various national climate centers dedicated to gathering delayed-mode as well as real-time data. However, the assembly of rainfall data from distributed sites of varying quality and record duration into a consolidated data set of precipitation estimates of known and acceptable quality is perhaps more like the process envisioned for the observing system.

DACs have been key elements of TOGA and WOCE and, through the GTSPP, have been involved in the processing of real-time as well as delayed-mode data. For these research programs, the attributes of DACs include:

- a clearly identified need for the particular data (to meet a goal);
- systematic collection to accepted standards and accuracy;
- involvement of both research institutions and national data centers;
- involvement of scientists experienced and skillful in the collection and use of the data;
- subjective and objective quality control procedures;
- procedures for tracking data flow, transferring and exchanging of data, collecting metadata and other documentation on the data, and interaction and cooperation with DIUs and archive centers.

The DACs created for the observing system should possess all these attributes. In research programs, DACs usually specialize in a particular field (e.g., upper ocean thermal data) or platform (e.g., subsurface floats). For the observing system, it is reasonable to expect that this experience can be used to consolidate the functions into more general, operational entities aligned to the goals and products of the observing system. This does not mean a lessening of the emphasis on scientific standards but seeks to make the observing system DACs span platforms and variables, and perhaps disciplines. This is commonplace in meteorology (though perhaps without the degree of scientific oversight so necessary for the ocean observing system). However, the needed DACs will require extensive experimentation during their implementation.

Figure VI.C.3-1 shows a functional diagram of WOCE Data Management (WCRP, 1988a) and the role played by WOCE DACs. For the observing system, the DACs will provide one path between the observation networks and the analysis systems and users. Some data will go directly to analysis systems without significant actions by the DACs (e.g., the use of subsurface temperature in near-real-time ocean analyses and ocean model data assimilation). Ideally, all data in an archive should be processed through a DAC in order to assure "Observing System Standard" data.

Quality control. In simple terms, quality control means the identification of erroneous data. In oceanography this is not a straightforward task. The definition of acceptable quality differs with the application and depends on the ultimate use of the product. For example, if salinity measurements are to be useful in models of the tropical ocean or in determining water masses they must be accurate to at least 0.01. However, for monitoring North Atlantic, convection which is sensitive to surface "capping" by freshwater run-off and/or alteration of the precipitation-evaporation-ice melt balance, it may be acceptable to map surface salinity at much less accuracy; while for monitoring water mass changes in the deep ocean, greater accuracy will be needed. Similar distinctions can be made for ocean temperature (real-time use versus detection of long-term climate change).

There are several phases in quality control, which are not necessarily always performed in the same sequence. The first phase involves checking the description of the data (time taken, location, etc.);

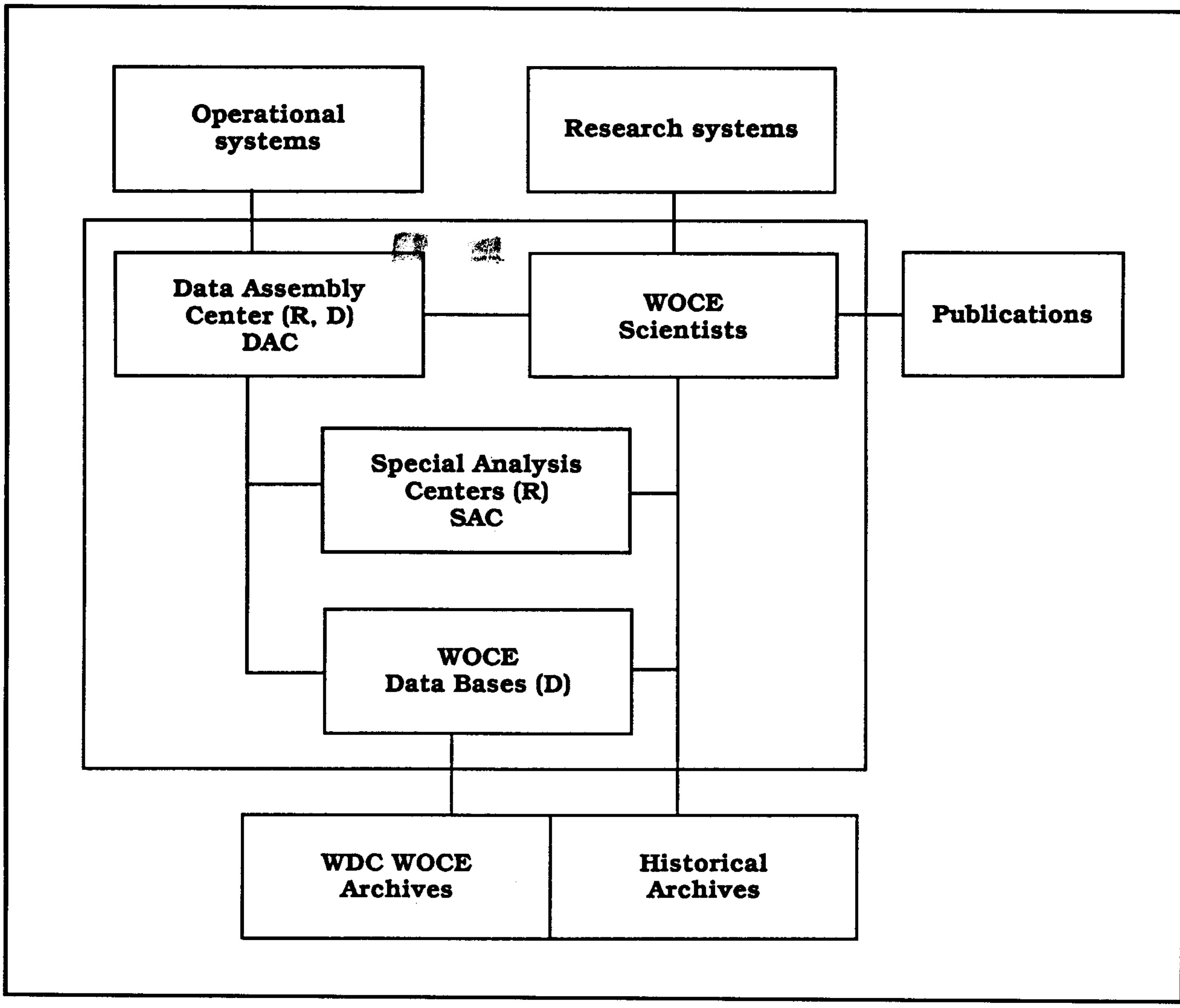



Figure VI.C.3-1. A functional diagram of WOCE Data Management (from WCRP, 1988a). The Data Assembly Centers assemble data from both operational and research sources and, with guidance from research scientists, provide improved data sets to the Special Analysis Centers and World Data Centers.

the process might be described as "editing". In some cases this can be automated, in other cases it is more effective to use an interactive graphical interface. An example of latter is the system used at the Marine Environmental Data Centre in Canada for checking real-time ocean data (WOCE, 1993).

The second phase involves quick-look ocean analysis and objective quality control systems where the data are tested against various independent estimates of the field and accepted/rejected depending upon the degree of consistency. Such systems depend on the quality of other information (e.g., climatology) and on the analysis system and/or model used for data assimilation. Data may be rejected simply because they are surplus to the information requirement or because they are inconsistent with some, perhaps biased, other estimate. Such systems may be a useful guide for determining whether data are of "Observing System Standard" but they are not, at this point in time, a substitute for scientific quality control.

The third phase involves scientific quality. There exist many different definitions of what constitutes "scientific quality" (e.g., WOCE, 1993) and there is unlikely to be a single definition which will withstand changing levels of scientific understanding and new applications. For the purposes of the ocean observing system, "scientific quality" is assumed to mean that the data have been subjected to objective and subjective scrutiny that, in the present context of scientific "best practice" and scientific understanding, adjudged the information to be a good sample of the actual oceanographic conditions. Bailey et al. (1994) provide an example of developing a systematic approach to scientific quality control of XBT data. No matter how this assessment is made it is ultimately subjective since the boundaries between "good" and "bad" data are not rigidly definable and different groups will make different interpretations.

The "Observing System Standard" for various data types will inevitably evolve as scientific practices, understanding and technology change. It depends most strongly on experience. Only now is there beginning to be some agreement on what constitutes scientific quality for ocean temperature profiles, largely through the efforts of the GTSPP and TOGA and WOCE. Even this may need to be moderated for non-climate applications. Programs such as the VSOP-NA (Kent and Taylor, 1991; Kent et al., 1991) are required to understand the vagaries of instrumentation deployed under operational conditions. The observing system is designed to include many less-conventional types of data, such as float, drifter and biogeochemical data, and the quality control of such data must be regarded as experimental initially.

### VI.C.4. Archiving, data bases, and data information

Access and distribution. The observing system will rely on a distributed system for information distribution and access. GCOS DMTT (1994) discuss various issues involved with establishing an effective distributed data base and present several examples on how it might operate for different types of users. They note that it should be planned with a visionary outlook so that future needs and technological advances can be accommodated. Weller and Dickey (1992) provide some insight into the potential for collaboratories in oceanography, a concept that is in some ways a research prototype of a distributed data access and archiving system.

The conceptual integrated data access system presented by GCOS DMTT (1994) is represented schematically in Figure VI.C.4-1. The data centers will operate independently. The first level of entry to each data center must comprise a standard set of functions which allow the client to see what data are held and to access descriptions of the data sets (dates, locations, etc.). In addition, one or more DIUs may be established with up-to-date data directories and data descriptions provided by data centers either on the network or off-line (see the DIU discussion to follow). Having established the availability of the required information, the user will then either directly download the information, prompt the server system to deliver the data after having first collected it from connected on-line media ("near-line"), or order the data to be gathered off-line and delivered in a convenient form.

GCOS DMTT (1994) discuss the functional requirements and conceptual design of a GCOS On-Line Data System, referred to as "GOLDS". Much of that discussion is directly applicable here and will not be elaborated on. Prototypes of "GOLDS" centers already exist in the oceanographic climate community. For example, the TOGA TAO display software and data access system provides access to textual, binary and graphical representations of the TAO data, either working directly through the TAO data base or by operating TAO software at the local site.

Metadata. Metadata can be regarded as information that describes data. They provide the information that users require to determine how the data were collected and subsequently processed. Metadata are particularly critical for climate data since the quality and durability of information collected over extended periods depends on, among other things, detailed knowledge of the instruments and techniques that were used to collect the data, the data sampling rates, the methods used for calibration and quality control, and the degree of scientific oversight and assessment during processing.

In some cases, it may be best to keep metadata attached to individual records as headers (e.g., instrument calibration, etc. on a CTD cast), adding "history" records as necessary to inform the user of any subsequent processing steps and any changes made to the data record. In other cases the metadata may be kept separately from data records if, for example, they are common to many data records.

In Section VI.C.2 some of the issues relating to standards and formats in data management were discussed. In general, there is no accepted single standard for metadata and other documentation. This should not, however, detract attention from the need to maintain adequate documentation for all observing system data as part of the information management system.

Data Information Units (DIUs). DIUs have been an integral element of recent climate research program information management strategies (e.g., WOCE and TOGA COARE). DIUs are in essence half-way houses between the user who is seeking data, and the (distributed) data base on which the required data resides. For a mature information management system, the DIU would be part of the data access and distribution system, much as discussed in the conceptual design for "GOLDS" (GCOS DMTT, 1994). However, given the relative immaturity of the data access and distribution systems for climate data, it probably is desirable for the initial observing system to establish one or more DIUs as separate units—perhaps aligned with the goals presented in Section III. As the system matures, the DIUs would blend in with the general data access and distribution activities.

The DIUs will provide information on the information management system itself and on data holdings and access methods for all observing system data. In the context of the conceptual observing system design presented in this report, the DIU will monitor and record all information flow associated with the various observational and processing elements, and will provide a directory for users to the depositories of this information.

Permanent archives. It is critical that permanent depositories for data be maintained as part of the observing system information management strategy. Section VI.C.3 discussed some of the issues relevant to maintaining such archives. The lasting and enduring value of data may not always be obvious (e.g., data initially classed as "bad" may be reclassified on the basis of improved scientific knowledge). Difficult decisions need to be made whenever archive resources are limited.

As a general principle, unless information can definitely be classified as useless, the data and associated documentation should be stored permanently and the integrity of the information maintained. Critical information should be duplicated at two or more sites. It is important that data centers maintain up-to-date directories of data holdings and routinely check on the actual availability of information in their data base. An up-to-date directory pointer for a tape or other media that have deteriorated creates the potential for permanent loss of information.

### VI.C.5. Products and application centers

The definition of Level III data as products of an analysis system, such as gridded SST fields, was given in Section VI.B.3. Scientists and application centers (defined below) will be the main users of Level III products although they will be of value to a wider user community. In contrast, Level IV products will be tailored to specific applications. For example, policy decisions on the possible impacts of an enhanced greenhouse effect will require, among other things, estimates of likely sea level changes. Decision makers will not be interested in the four-dimensional fields of a coupled ocean-atmosphere model but will demand generalized summaries of expected changes, perhaps at regional resolution; this information might be shown in a single graph.

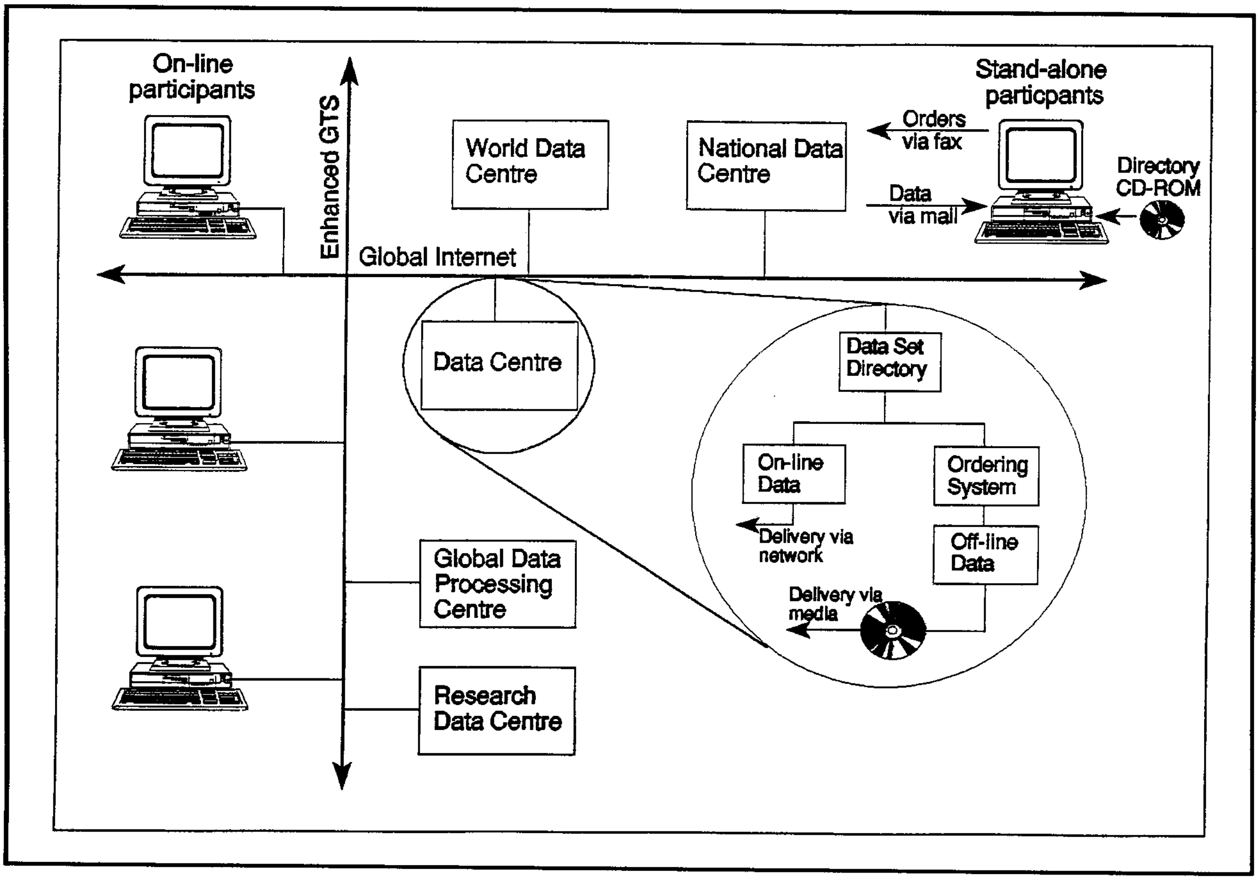



Figure VI.C.4-1. A conceptual data access system as envisaged by the GCOS Data Management Task Team (GCOS DMTT, 1994). The data center is at the hub and can serve clients with on-line or off-line access; it provides information (metadata, actual data) through these same on-line or off-line systems or through other convenient means (e.g., CD ROMs).

Application centers. Such a distillation of complex information for a target audience will require specialist application groups/centers. At present, assessments of long-term climate change have been managed under the auspices of IPCC. In the future specialist groups might be devoted to regular assessments of ocean climate and the interpretation of observations and model simulations to form long-term climate change outlooks (see also Section VIII.C).

The reinterpretation of Level III data into Level IV products occurs at present during the assessment of seasonal and interannual climate change. Section I.B.1 presented several examples of national climate centers that gather ocean data and analyses for the purposes of forming short-term climate outlooks.

The proposal for a Seasonal-to-Interannual Climate Prediction Program (SCPP) (Section VIII.C.3) explicitly identifies application centers as an integral part of the system for developing prediction models and providing forecasts to users. Among other things the application centers would develop regional assessment capabilities for specific environments and construct products to support the end-user community in decision making. Figure VI.C.5-1 shows schematically the role of application centers envisioned.

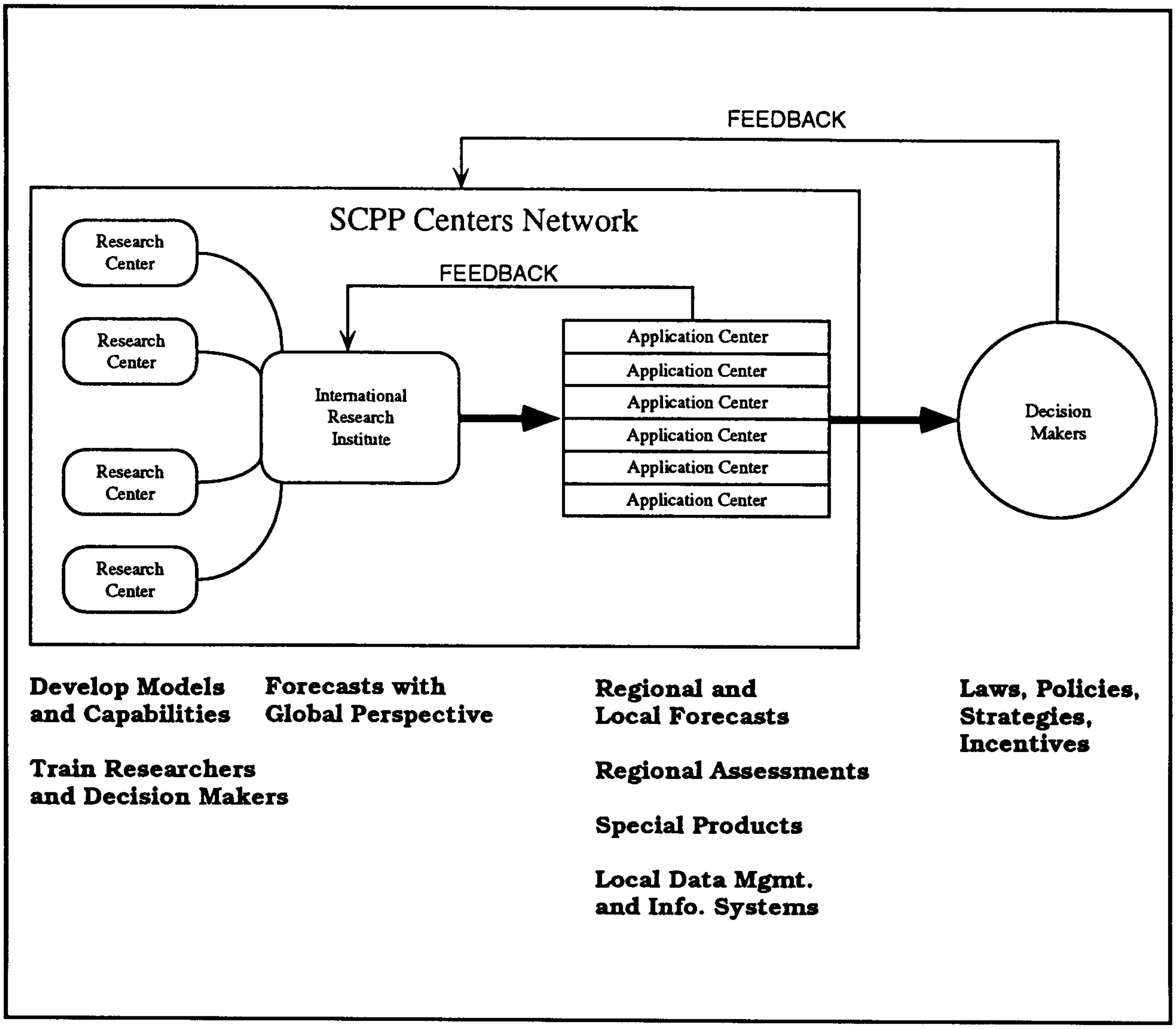



Figure VI.C.5-1. Programmatic architecture proposed for a SCPP. The SCPP centers would gain knowledge from global climate research programs and data from the global ocean observing system for climate. Results or products are indicated below each type of entity. (Adapted from a proposal for an International Research Institute for Climate Prediction prepared by a task group chaired by A. D. Moura, 1992, figure 5.3)

### VI.C.6. Management and policy

Management. The operation of the information management system will be the responsibility of the various technical and scientific committees charged with implementing and overseeing the observation system (Section VII.D discusses this in more detail). It is important to note that the information management system will be implemented largely through existing national and international agencies and organizations. In this sense, its implementation faces the same challenges as the observing elements.

Initially, oversight of the information management system might be met through careful coordination between existing bodies. However, in time, we can expect the responsibilities to reach a magnitude that would require a dedicated, specialist group. This might be a Data Management Panel, as used in programs like WOCE and recommended for GCOS (GCOS DMTT, 1994). Alternatively, it might be a responsibility of a Commission for Basic Ocean Systems (like the Commission for Basic Systems of WWW, see Section VII.D), with close links to its meteorological counterpart, and with specialist technical groups as required for implementing, evaluating and enhancing various elements of the information management system.

Information exchange policy. A policy on information exchange is required for the ocean observing system for climate. Its success will depend upon the willingness of participants to exchange information; any delay in this exchange effectively reduces the amount of information available. It is also important that the policy advocates the advantages of providing and exchanging information free of added charges for the benefit of all.

The principles of data exchange were set out in Section VI.A.2 and in the goals of Section VI.A.3. GCOS DMTT (1994) have proposed that GCOS contributors and users follow several basic tenets in regard to managing GCOS data in order to ensure an "unrestricted international exchange of GCOS data for peaceful, non-commercial, global scientific and applications purposes." The ocean observing system for climate will depend on full and open sharing and exchange of information for the benefit of all participants. It is inevitable that the commercial value of some information and products will work to undermine this ideal, much as is happening in meteorology. However, it is essential that the "owners" and managers of the observing system never lose sight of the overriding benefits that free and open exchange of information will provide in meeting the objective of monitoring and understanding the changing climate of the global ocean.

# VII. SYSTEM ORGANIZATION AND EVOLUTION

## VII.A. Enabling Research

The process of designing an ocean observing system for climate involves identifying goals for which the system is to be implemented based on societal needs and on current scientific understanding. Then the process must prioritize the variables to be measured based on the system subgoals, determine the time and space scales on which those variables must be measured, and devise suitable sampling schemes based on available resources and technologies. This process must be evolutionary because our knowledge of the ocean's role in climate is imperfect, the full spectrum of oceanic variability has not been resolved, the technologies available to us are limited in their capabilities, and the resources to implement an observing system are finite. An observing system design should therefore be flexible enough to take advantage of advances in science and technology, the latter of which is discussed in Section VII.B. This section focuses on the concept of enabling research, by which we mean research that leads to a better scientific understanding of observing system design criteria, and to a better application of the data provided by the observing system.

Enabling research may be undertaken for the explicit purpose of refining the observing system design. Examples of such research include correlation scale analyses, observing system simulation experiments, and development of improved data assimilation and initialization schemes for climate models. Such research also might determine the extent to which oceanic data, once assimilated into dynamical models, influence model-based analyses and predictions. Studies such as these, because they are targeted toward specific observational issues, can be very effective in providing a quantitative basis for optimizing sampling strategies.

Enabling research also may be undertaken for the primary purpose of describing or understanding a phenomenon, process, or collection of processes at work in the ocean (i.e., basic research). This research may have only secondary or peripheral relationship to the observing system design; however, its consequences may nonetheless have profound impacts on sampling strategies. This research may be theoretical, observational, empirical and/or model-based in character. Research may also be directed toward the applications of the data. Better understanding of the processes and the correlations, or better understanding of the kinds of syntheses and distillations that are reasonable, can lead to much improved data products and better applications. The most compelling design implications usually result from a convergence of opinion based on all these separate threads of investigation.

TOGA offers a good example of how research has influenced, and continues to influence, the design of an observing system for ENSO prediction. Design of the TOGA observing system was based on model, observational and empirical studies, with emphasis on measurements of surface winds, SST, upper ocean temperature, sea level (a proxy for heat content), and upper ocean currents. Real-time data telemetry was given a high priority to support efforts in climate system monitoring and prediction. Implementation of the observing system relied on adaptation of existing technologies and development of new instrumentation; at present it consists of a basin scale moored array (TOGA-TAO) for winds, upper ocean temperatures, and currents; a Volunteer Observing Ship XBT network for upper ocean temperature; an island and coastal tide gauge network for sea level, and drifting buoys for SST and near surface currents. Satellite measurements, most notably those from NOAA's polar orbiting weather satellites for SST, and those from altimeters (e.g., Geosat and TOPEX/POSEIDON) for sea level, have likewise been invaluable.

The design of the TOGA observing system will likely change in response to advances in our understanding of climate dynamics. For example, it has been hypothesized that shallow haloclines in the western Pacific warm pool are essential for understanding the upper ocean heat balance. The recent TOGA-COARE experiment was designed in part to test this hypothesis which, if proven correct, would argue for systematic, long term salinity measurements in the equatorial Pacific. Similarly, predictability experiments being performed with sophisticated coupled ocean-atmosphere models may suggest that a greater (or lesser) density of in situ observations are required for initializing ENSO forecasts, based on the dynamics of the climate system.

The scientific knowledge and understanding regarding many of the other subgoals of the ocean observing system for climate are not as advanced as for the ENSO prediction problem. One example is our level of understanding of the role of the ocean in the carbon cycle and our limited knowledge of what measurements are needed. JGOFS is an ongoing international research program attempting to provide some of the needed answers. Another example is our lack of knowledge of the time scales and amplitudes of deep ocean circulation variability which limits our ability to formulate and validate numerical simulations of the global ocean circulation. WOCE is one ongoing research program which will provide such data.

WOCE, TOGA, JGOFS, GEWEX, CLIVAR and other global change research programs of the WCRP and the IGBP will all add scientific knowledge and understanding needed to advance the development of the observing system. It is also certain that even though the ocean observing system for climate is not designed for research, the data derived will stimulate research and provide understanding of the climate system in ways that are not now apparent. Scientific information will never be complete and, for that reason, the observing system must remain as an evolutionary system and support for the underpinning research programs must continue.

This discussion of the importance of enabling research should not be interpreted as meaning that the design of the observing system must await additional research. In fact, most of the observing system is quite readily designed at this time, but current and future research will allow many refinements and efficiencies.

Some research areas of particular value are:
- observing system simulation experiments;
- assimilation of data providing integral constraints;
- dynamics of the climate system;
- impact of improved bottom bathymetry;
- time and space scales of variability; and
- possible "key indicators" of climate change (e.g., Arctic air temperatures or Gulf Stream transport).

## VII.B. Enabling Technology

### VII.B.1. Introduction

The initial measurements of the ocean observing system for climate must be made using existing technologies. However, improvements to such technologies, including logistics and communication systems, would result in cost savings and improved performance. Moreover, a number of developing technologies are almost ready for long-term, systematic use, while others are only now emerging but may be useful in the not so distant future. Finally, potential technologies are desired that are not now on the drawing boards. All these classes of technologies will eventually be used to make the routine measurements needed for the full development of the observing system. In this section, we discuss the role of technology development within the system.

If fostered and adequately supported, technological advances will have an impact on the observing system in various ways. For example, they will allow measurement of new variables and enable more complete measurements of needed fields and processes through higher sampling densities.

Moreover, improvements to the accuracy, stability, and longevity of measurement systems are anticipated. In some instances, new technology also may allow existing observational requirements of the observing system to be carried out at lower cost. Many of these improvements will come through the continuing refinement and evolution of existing measurement systems (e.g., reflecting advances in power storage, low power electronics, and data telemetry). Progress also will occur when new technologies emerge, as for example, in stable, low-power sensors for $pCO_2$ for use on moorings.

In this section, examples are given of existing technologies to be made operational or improved, developing technologies, and potential technologies for the future. Then a tabular summary of existing, developing, and potential technologies is presented. Finally, ways in which enabling technologies should be fostered and incorporated are suggested.

## VII.B.2. Examples of technologies

### VII.B.2.a. Existing technologies

TAO array. One example of how technological refinement has benefited climate studies is the development of the ATLAS wind and thermistor chain mooring (Hayes et al., 1991). The ATLAS design is similar to that of other taut-line surface moorings previously used in climate studies. However, ATLAS was purposefully designed for longer life and lower cost, so that large numbers of moorings could be deployed in a coherent basin-scale array (i.e., TOGA-TAO). In addition, ATLAS was designed to transmit all its data in real-time for day-to-day monitoring of the tropical ocean atmosphere system, and for assimilation into oceanic and atmospheric models used for climate analysis and prediction.

ALACE. An autonomous profiler is already providing cost effective vertical profile information over a wide area of the Pacific. As part of WOCE, a new type of Lagrangian float has been developed by R. Davis and D. Webb. ALACE is a neutrally buoyant float which periodically surfaces from its parking depth (as deep as 2000 m) to transmit its position via Argos. This occurs from once a week to once a month; the resulting series of positions give a coarse resolution float track suitable for large scale circulation studies (Figure VII.B.2-1). Over 300 ALACEs have been deployed. On many floats the vertical temperature profile during surfacing is transmitted as well. Under test is a version which also records the salinity profile. With lifetimes of up to five years and a modest price such autonomous instruments are now envisioned as a cost-effective means for obtaining temperature and salinity profiles, and it seems feasible to deploy sufficient numbers to achieve the global coverage required. As an example, a fleet of about 10,000 ALACEs would be adequate to provide a vertical profile every two weeks for every 300 km (long.) x 100 km (lat.) rectangle in the global ocean between 60°N and 60°S. For 500-km x 500-km resolution, about 1100 floats would be required. This assumes deployment from ships of opportunity and a strategy that avoids oversampling of float convergence regions. Because data are available in real time, such autonomous vehicles promise to become a practical tool for monitoring the baroclinic structure of the ice-free upper ocean.

### VII.B.2.b. Developing technologies

Rapid CTD profiling. Two distinct approaches for rapid CTD profiling have been developed, tested and are now ready for initial research utilization. Both are very promising as monitoring technologies.

With the objective of obtaining rapid high-quality, full-depth profiles of temperature and salinity from a free instrument, the Fast Hydrographic Profiler (FHP) has been developed by Albert Bradley, Joshua Hoyt and others at the Woods Hole Oceanographic Institution. This instrument

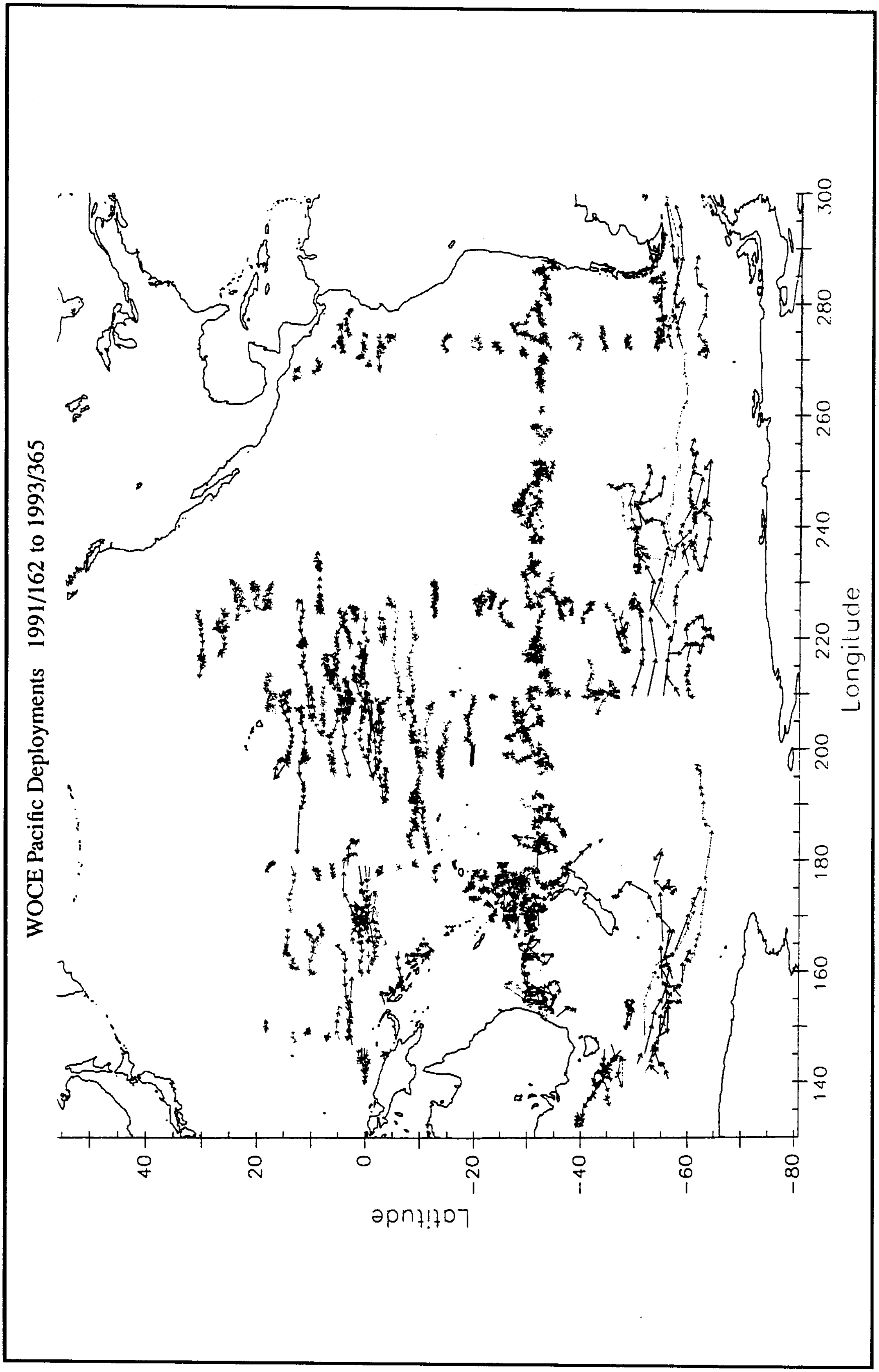



Figure VII.B.2-1. Trajectories of 275 ALACE floats deployed as part of WOCE near 1000-m depth. Each arrow represents the displacement over one submerged period of 26 days; surface drift or missing fixes cause gaps between arrows. A few floats report temperature profiles at each ascent; one also reports salinity.

removes the need for an oceanographic winch, returning profiles from 4000 m depth with a return-trip travel time of about 25 minutes; the total time required for deployment, profiling, and recovery in full ocean depth is approximately 45 minutes, resulting in a major saving of ship time.

The sensors used on the FHP are standard Neil Brown Mark III sensors; the CTD electronics are also state of the art. Since 1986 this instrument has been thoroughly tested. Although some problems remain and improvements in handling are foreseen, the FHP now appears ready for regular deployments in research or monitoring mode. A review of its development and performance is found in Peterson and Chereskin (1994).

Jean-Guy Dessureault at Bedford Institute of Oceanography has developed a CTD system that can be deployed and retrieved while a vessel is underway, analogous to the old mechanical bathythermograph systems. A working system exists that is ready for use on research vessels. The ultimate goal is a system for use from VOS under bridge control; at present a technician is still required on board. A description is given by Dessureault and Clarke (1994).

Satellite data relay. At present, the ocean climate community relies heavily on Service Argos for real-time positioning and transmission of data from platforms deployed in the ocean. System Argos uses NOAA's polar orbiting weather satellites and is based on concepts that are 20 years old. Transmissions are bandwidth limited, relatively expensive, and allow for one-way communication only. While adequate for many needs now and some needs in the future, it is clear that this system will not meet the more demanding requirements for future oceanographic data telemetry. Alternatives based on adaptation of existing technologies or development of new technologies (e.g., low cost, low power GPS receivers for positioning, and two-way, broad-bandwidth communication via cellular phone) should significantly enhance present capabilities. Section VI.C.1 reviews many of the likely options. Progress on this issue is essential for GOOS/GCOS; and fortunately, it appears that a number of commercial satellite systems will be available to fill this need (Motorola Iridium, Loral Globalstar, Teledesic, etc.). However, data telemetry will remain a priority development issue if the planned systems are not realized or are not affordable.

Acoustic thermometry. Acoustic thermometry, or more generally, ocean acoustic tomography, is a tool for remote sensing of the ocean interior. It exploits the transparency of the ocean to low frequency sound and the sensitivity of acoustic propagation to the ocean temperature and current fields to make rapidly repeated measurements of spatially averaged quantities, such as heat content. Vertical resolution is obtained by resolving arrivals of acoustic signal that have followed different ray paths, traversing different parts of the water column. Horizontal resolution is determined by the number and location of the acoustic sources and receivers deployed in the ocean, and preliminary experiments have been done on scales from 10s of kilometers to 18,000 km.

Munk and Wunsch (1982) noted the potential for global mapping of internal ocean temperature with a large enough network of sources and receivers. Munk and Forbes (1989) suggested that global scale acoustic transmissions could be used to monitor global ocean warming. A warming of 0.005°C/yr would produce a decrease in travel time of 0.2 sec/yr for 10,000 km path length. As a feasibility test, acoustic signals were transmitted from Heard Island in the southern Indian Ocean in January 1991 (Baggeroer and Munk, 1992; Munk et al., 1994). These signals were received on both coasts of North America, and the signal-to-noise ratios achieved supported the goal of measuring travel times accurately enough to measure large-scale thermal variability in the ocean (Munk et al., 1994). Implementation of a large scale acoustic array is planned under the Acoustic Thermometry of Ocean Climate (ATOC) project. The goal of ATOC is to quantitatively test the ability of acoustic techniques to measure variability in thermal structure and heat content over 3,000 to 10,000 km and seasonal scales.

A number of regional acoustic array deployments have been conducted. Areas studied include the Greenland Sea, the Gulf Stream, the interior of the central gyre of the North Atlantic, and the

Mediterranean Sea. Three-dimensional inversions of data from the Mediterranean showed the formation and evolution of convective chimney structures on scales of 30 to 40 km (Morawitz et al., 1994; Gaillard, 1994). The work near the Gulf Stream showed eddy energy radiating southward away from the boundary current as packets of Rossby waves (Chester, 1993; Chester et al., 1994; Chester and Malanotti-Rizzoli, 1994).

Acoustic tomography appears to have the potential for long term observations over a range of scales. At present, a number of existing receivers, such as the U.S. Navy SOSUS array, are available to complement those that might be deployed specifically for GOOS. Acoustic sources are under development that would last 10 years. A global monitoring system could be constructed using two to three sources per ocean basin, existing receivers, and an additional five to six receivers in each basin. As an additional benefit, a global acoustic array could also serve as a subsurface navigation system for SOFAR, RAFOS, and other types of floats.

Slocum. One of the inspiring visions for the future of ocean monitoring was provided by Stommel (1989). He described a fleet of 1000 "Slocums", autonomous profilers of ocean properties, which glide around the ocean making six soundings a day in the year 2021. Some would be programmed to occupy sections; others to remain in place. All transmit their data and are controlled by communication satellites. Their function is to monitor and explore the global ocean. He described how they would calibrate one another, to assure data quality and continuity in detecting ocean climate change. At present a modest development effort on Slocum is underway at Webb Research Corp. (Falmouth, MA). Both the gliding/navigating system and a method for extraction of power for buoyancy changes from the temperature gradient in the thermocline are under development. A battery-powered, continuously-moving Slocum would have a life time of only 40 days, but the thermally powered model is projected to have a five-year life time. Since the potential horizontal speed of the Slocum is low, the best application of the gliding system may be simply for station keeping rather than transects. As small, stable, low-power CTD sensors are now available, it appears that Stommel's envisioned system is well within reach.

Autosub. The Autosub is an unmanned autonomous vehicle under development by the Natural Environmental Research Council in the U.K. It is intended to have the capability for routine collection of physical, chemical and geophysical data for use in observing systems and future marine science programs. This is a significant, ongoing development that involves the integration into a new vehicle of new developments in many key subsystems: pressure hull, mission management system, surfacing buoyancy system, telemetry and collision avoidance system, and propulsion and control system. Two configurations are envisioned: one for gathering wide-area hydrography and one for remote geophysical exploration of the ocean floor. The hydrographic version is intended for collection of subsurface data by regularly profiling while traveling along preset ocean transects, although the preliminary design range is only 1200 km. Like ALACE, this device is planned to have its position fixed and to transmit data via satellite when it surfaces between profiles.

Electromagnetic sensors. Electromagnetic devices are able to provide information about oceanic currents and/or transport and/or averaged temperatures, because sea water is an electrolyte and the earth has both magnetic and electric fields. The electromagnetic technology with which there is the most experience is the monitoring of resistance and voltage difference across ocean floor cables. Larsen (1992) reports on a decade of Gulf Stream cable measurements that provide baseline knowledge of interannual Gulf Stream variability. This information would be prohibitively expensive to obtain if collected by conventional current measuring devices. Many other ocean cables are in place and available for monitoring the transport across their terminations. In some cases special short term surveys are required to permit interpretation of the voltages in terms of mass transport but, once done, these cables can give information for decades to come. Many cables of interest are due to be cut or otherwise abandoned in the coming years; in most cases it is quite expensive to re-connect. A panel of experts might be convened to identify the cables of greatest potential interest and to request of the relevant companies that these cables not be terminated or abandoned for a decade to permit the ocean community time to decide how to make best use of these valuable instruments.

Other electromagnetic technologies for current and transport measurement are in varying stages of development and deployment (e.g., Sanford et al., 1990; Sanford et al., 1993; Sanford et al., 1995a, b; Filloux, 1974, 1987). In Figure VII.B.2-2 is a summary from T. Sanford (personal communication) of ocean velocity sensors based on motional induction. These instruments certainly comprise an area of developing technology that merits watching.

Ice mass estimation. An accurate estimate of ice mass in the Arctic Ocean would provide a valuable signal for monitoring climate change in this polar region. Many active sonar methods have been proposed to this end, but a passive method may be sufficient. The ice is driven continuously by a variable stress field, which arises from thermal effects, wind, and currents. The applied stresses cause the ice to fracture on scales ranging from millimeters to kilometers; the fracturing process, in turn, produces acoustic emissions radiating into the water column below the ice. The temporal and spectral character of these emissions are affected by the thickness of the ice through at least three physical mechanisms; these mechanisms are areas of active research for Prof. J. Robert Fricke at MIT. By monitoring the acoustic emissions, it is possible to invert for ice thickness in a region of order ten square kilometers near any given monitoring station. Preliminary results from an experiment in the Beaufort Sea during March 1994 demonstrate the feasibility of the approach. At this time only one of the three possible mechanisms has been used to invert the data; continuing research will explore the applicability of the other two.

Assuming ice thickness can be estimated in patches of 10 square kilometers, it is then possible to estimate total ice mass through spatial integration. The long term vision is that data for this integration will be gathered by a fleet of inexpensive autonomous underwater vehicles (AUVs) cruising beneath the ice on a continuous basis. The continuous deployment will provide data for estimating both spatial and temporal ice mass variability. Each vehicle will be instrumented with hydrophones and recording equipment. The technology for off-loading data and refueling the AUVs at underwater docks is currently being developed under sponsorship of ONR and others. In the next several years, this technology may be sufficiently mature to support preliminary deployments of AUVs for monitoring Arctic acoustic emissions. With this data, estimates of ice mass over spatial scales of 1000s of square kilometers should be possible, even with primitive AUV systems, and in the long term, estimates for the entire Arctic basin.

### VII.B.2.c. Potential technologies

There is great promise for future enabling technology developments to enhance our ability to observe, understand, and predict climate variability and change. Without attempting to be comprehensive, we cite here a few examples to illustrate the point.

Acoustic data telemetry. For many applications an instrument can be deployed on the bottom or on a subsurface mooring at much lower cost than a surface mooring. Surface moorings must be designed for increased line tensions and wear because of surface wave forcing; they are also subject to loss by vandalism. However, though cheaper to deploy, a subsurface mooring complicates the task of data telemetry since no RF link can be established. Abandoned submarine cables could provide the data link in a few instances, but the number of sites would be limited, as the shielding on such cables prevents the use of inductive coupling devices along the cable. A new development with great potential impact is the acoustic modem. Since acoustic energy propagates well in water, the potential for communications has long been recognized; however, the slow speed of sound and its variation with temperature and pressure, leads to multiple pathways between source and receiver. This problem leads to reverberation (echoes) which limited earlier systems to

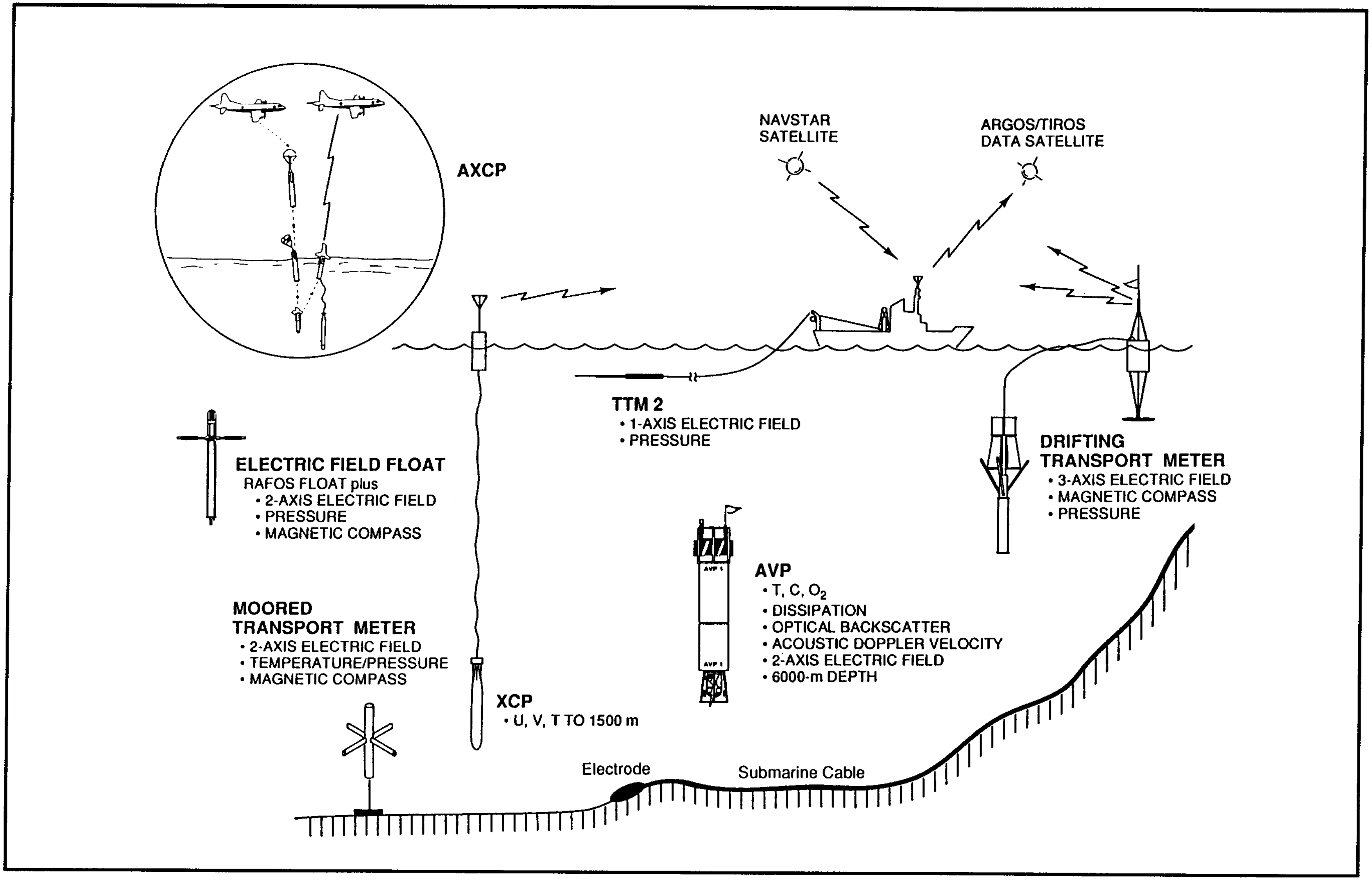



Figure VII.B.2-2. Ocean velocity sensors based on motional induction: XCP is expendable current profiler; AXCP is airborne expendable current profiler; TTM is towed transport meter; and AVP is absolute velocity profiles. (Source is Tom Sanford, personal communication, 1993.)

low data rates and short distances. Developments in low-cost digital signal processing hardware in the late 1980s have provided solutions to these significant problems (Catipovic et al., 1993; Travis, 1994). Modern systems can now filter out noise and even make use of late-arriving echoes to check the accuracy of the original signal. Systems can be constructed with limited power consumption, though the data rate decreases for transmissions over greater distances. Presently available acoustic modems can provide 1000 bit-km/Joule of battery power; and 10,000 bit-km/Joule should be possible. This translates into useful data rates with modest battery packs over ranges of 10 to 100s of kilometers.

Three application areas can be identified:

1. Long range systems (20-2000 km) operating at carrier frequencies of 500 Hz to 10 kHz. Data rates of 100 bits/sec at 1000 km and 10,000 bits/sec at 20 km are currently achievable.
2. Medium range systems operate in the range of 1-10 km and use frequencies of 10-100 kHz. Data rates of 10-50 kbits/sec are feasible.
3. Short range systems operate at distance less than 1 km and can reach 100 kbits/sec.

Local area networks of such modems can be assembled incorporating both moored instruments and autonomous vehicles (Curtin et al., 1993). The most efficient transmission protocol for such networks will vary with the application, since each situation will have different transmission delays and power constraints (which forces one to minimize handshaking and lower the duty cycle of each modem). An underwater acoustic network could be linked to the Internet via RF or land link, so that instruments will be able to mail data back to the desktop workstations of their owners. Guidance and sampling control of AUVs and stationary instruments are obvious applications of two way communication. Presently, an undersea network of acoustic modems is transmitting data from a dozen bottom mounted instruments in Monterey Canyon. Other monitoring networks are planned for Buzzards Bay, ice-covered Arctic seas, and for the convectively active Labrador Sea. The disadvantages of the acoustic approach are the relative expense and higher power requirements of the equipment, since the ocean sound channel is much noisier and more complicated than an RF channel. This option is best used when the lack of a surface expression (required for RF) is an essential requirement of the instrumentation.

Of particular interest for an ocean observing system for climate are the greater ranges that would be achievable with lower carrier frequencies (200 HZ). At such frequencies it would be possible to receive transmissions through the listening stations of the Integrated Undersea Surveillance System (IUSS), operated by the US Navy. A low frequency acoustic modem could have a significant range (several thousand kilometers) and a low, but climatically useful, data rate. This would enable the deployment of long lived deep-sea monitoring instruments, that need not be recovered. The savings in ship time on this feature alone could more than pay for the modem, and the advantage of real-time data acquisition makes this a very attractive deployment scheme for long term deployments. A key to success is the development of a sufficiently low cost, low frequency sound source. Also, while the IUSS is a classified system, it would be possible to provide scientists with the data stream of interest without any loss of security. Acoustic telemetry coverage over much of the Northern Hemisphere oceans may be achievable.

<u>Stable $pCO_2$ and nutrient sensors</u>. Automated systems, when installed either on moorings or Lagrangian drifters, are particularly well adapted to produce continuous time series of measurements of physical, chemical, or biological parameters. Their use could greatly supplement the capability offered by VOS. They offer the possibility to extend geographical and temporal coverage to regions remote from merchant ship lines. In addition, measurement systems on fixed and drifting platforms resolve shorter time scale processes than can be measured from a ship steaming at 15 kt or more.

For such instruments, a lifetime of at least one year is a reasonable requisite because most of the quantities of interest, either physical or biogeochemical, have a seasonal cycle. This puts constraints on the quality of various sensors that can be used, mainly because of the need for stability in time. Any drift of the instruments must be corrected over the working period of one year. This constraint is one of the major difficulties encountered today in the development of chemical sensors to measure nutrients or $pCO_2$. Problems of biofouling must be overcome for both biological (fluorescence) and chemical measurements.

Global SSS from space. Upper-ocean salinity is one of the key variables for climate-scale ocean variability. It may be as important for high latitude decadal circulation changes as the SST is for tropical interannual variability. Significant progress is being made on long-term measurements from in situ instruments, but there may never be enough instruments for resolution of fronts and other small-scale structures. A satellite remote sensing technique for SSS would be of great value. Unfortunately, the measurement of SSS from space requires very low microwave frequencies, and thus large antennas and footprints several hundred kilometers across. However, the measurement of even mean SSS over large areas may have utility for climate studies, if the accuracy is sufficiently high. This appears difficult, but is worth continued study.

In situ measurements for calibration of satellite data. Instruments installed on satellites either measure directly a property of the sea surface (e.g., irradiance) or measure some quantity related to the property of interest (e.g., a scatterometer measures a backscatter field which must be related to the wind vector through a given algorithm). In both cases, even for the simplest systems, it is always necessary to continually check the validity of the data provided by the satellites, which commonly operate for a period of several years.

Over the lifetimes of satellite missions, autonomous systems deployed in well-selected regions of the ocean would provide some of the required in situ data to complement and validate data from satellite instruments and would allow corrections when biases or drift in the satellite data sets are observed.

For the irradiance and the scatterometer mentioned above, the equipment required for installation on the autonomous platforms are temperature and wind sensors. The situation is less straightforward if we are interested in using ocean color as a proxy of the biological activity affecting the transport of carbon between the surface layers and the interior ocean. For this purpose, in situ systems giving simultaneous measurements of $pCO_2$, fluorescence, SST, and nutrients are needed, along with remotely-sensed ocean color, for use in models to estimate air-sea fluxes of $CO_2$ and the transfer of carbon between the atmosphere and the interior ocean.

### VII.B.3 Summary of technologies

To expand its understanding of the available technology for potential application to an ocean observing system for climate, the OOSDP distributed a questionnaire to many members of the international oceanographic community asking for opinions and suggestions regarding "enabling technologies" for the observing system. The questionnaire responses were quite diverse; some addressed issues of low priority for climate, although of potential interest for other components of GOOS. A copy of the questionnaire and a listing of respondents with topics addressed are included as Annex III.

A tabular summary of existing, developing, and potential technologies related to the ocean observing system for climate is included here as Table VII.B.3-1. It is based both on known technology and on the questionnaire responses. Table entries related to questionnaire responses are designated by a letter-number code after the entry; reference to Annex III will provide the originator of the response.

Table VII.B.3-1. Examples of existing, developing, and potential technologies for use in measuring climate variables or quantifiable aspects of the ocean climate system.

| | EXISTING TECHNOLOGIES | | | | Developing Technologies | Potential Technologies |
|---|---|---|---|---|---|---|
| | Principal Costs | | Improvements sought | Near Global Coverage | | |
| VARIABLES/TECHNOLOGIES | Capital | Recurrent | | | | |
| SST | | | | | | |
| ATSR | X | | | X | | |
| AVHRR | X | | | X | | |
| VOS measurements | | X | | | | |
| VOS improved measurements | | X | X | | X | |
| T on surface drifters | | X | | | | |
| TAO array | X | X | | | | |
| SSS | | | | | | |
| VOS Thermosalinographs | | X | | | | |
| S on surface drifters | | X | | | X | |
| S-Satellite (ESTAR) | | | | | | X |
| Upper Ocean T, S | | | | | | |
| XBT | | X | | | | |
| XCTD | | X | X | | | |
| Sea Soar | X | X | | | | |
| CTD profiler on VOS (D-2, F-2) | | | | | X | |
| Moored CTD Profiler (F-2, T-2) | | | | | X | |
| Surface moorings, e.g., TAO | X | X | | | | |
| Slocum (R-2) | | | | | X | |
| Autosub (C-5) | | | | | X | |
| T-Profiling ALACE | | X | | | | |
| S-Profiling ALACE | | | | | X | |
| Surface winds | | | | | | |
| NWP analyses | | X | | X | | |
| VOS observations | | X | | | | |
| SLP on drifting buoys (S.O.) | | X | | | | |
| TAO array in Pacific | X | X | | | | |
| Satellite scatterometer system | X | | | X | | |
| Improvements to VOS observations | | | X | | X | |
| SSM/I wind speeds | X | | X | X | | |
| Altimeter wind speeds | X | | X | X | | |

Table VII.B.3-1. Part 2 of 4.

| | EXISTING TECHNOLOGIES | | | | Developing Technologies | Potential Technologies |
|---|---|---|---|---|---|---|
| | Principal Costs | | Improvements sought | Near Global Coverage | | |
| VARIABLES/TECHNOLOGIES | Capital | Recurrent | | | | |
| Surface winds (continued) | | | | | | |
| Subsurface noise (M-3) | | X | X | | | |
| Surface heat fluxes | | | | | | |
| NWP analyses | | X | | X | | |
| VOS observations | | X | | | | |
| Moored buoys (TAO) (M-3) | X | X | | | | |
| Moored buoys (research) (H-1) | X | X | | | | |
| Satellite radiation measurements | X | | | X | | |
| Irradiance (M-1) | | X | X | | | |
| Surface water fluxes | | | | | | |
| Evaporation from VOS | | X | X | | | |
| Net water flux from NWP models | | X | | X | | |
| Precipitation: satellite | | | | | | |
| OLR | X | | X | X | | |
| SSM/I | X | | X | X | | |
| TRMM | | | | | X | |
| Precipitation: in situ | | | | | | |
| Optical rain gauges | | X | X | | | |
| Capacitive rain gauges | | X | X | | | |
| Subsurface noise (M-3) | | X | X | | | |
| Rain radar | X | | X | | | |
| Velocity | | | | | | |
| Drifters (C-1) | | X | | | | |
| SOFAR floats | | X | | | | |
| RAFOS floats | | X | | | | |
| ALACE type (M-4) | | X | X | | | |
| ADCP on VOS (A-2, K-1) | X | X | X | | | |
| ADCP (moored) (K-3) | X | X | X | | | |
| ADCP (lowered) | X | X | X | | | |
| E-M Cable (L-2, S-1) | X | | | | | |
| E-M, moored (C-2) | | X | X | | | |
| E-M, towed (S-1) | | X | X | | | |

Table VII.B.3-1. Part 3 of 4.

| | EXISTING TECHNOLOGIES | | | | Developing Technologies | Potential Technologies |
|---|---|---|---|---|---|---|
| | Principal Costs | | Improvements sought | Near Global Coverage | | |
| VARIABLES/TECHNOLOGIES | Capital | Recurrent | | | | |
| Velocity (continued) | | | | | | |
| E-M float (S-1) | | X | X | | | |
| Current meter (mechanical) (C-7) | | X | X | | | |
| Cur. meter (acoustic travel time) (B-3, B-4) | | X | X | | | |
| Reciprocal acoustic transmissions | | | | | X | |
| Dropsondes | | X | X | | | |
| Heat/freshwater content | | | | | | |
| VOS XBTs | | X | | | | |
| VOS XCTDs | | X | X | | | |
| Inverted echo sounder | | X | X | | | |
| Acoustic thermometry | | | | | X | |
| CTD Profiler on VOS | | | | | X | |
| Fast Hydrographic Profiler (B-2) | | | X | | X | |
| Moored CTD profiler (F-2, T-2) | | | | | X | |
| Fishing vessel CTD (G-4) | | X | X | | | |
| Heat and freshwater transport | | | | | | |
| CTD sections | | X | X | | | |
| Autosub | | | | | X | |
| Slocum | | | | | X | |
| XCTDs from VOS | | X | X | | | |
| Fast Hydrographic Profiler (B-2) | | | X | | X | |
| Sea Level | | | | | | |
| Tide gauges (M-2, P-1) | | X | | | | |
| Satellite Altimeter (G-2) | X | | | X | | |
| Bottom pressure gauges (M-2) | | X | X | | | |
| Sea Ice | | | | | | |
| Microwave satellites (W-1) | X | | | X | | |
| Ice drifters | | X | | | | |
| Moored upward-looking sonar | | X | | | | |
| Submarine ULS | | X | | | | |
| Subsurface noise (M-3) | | | | | X | |

Table VII.B.3-1. Part 4 of 4.

| | EXISTING TECHNOLOGIES | | | | Developing Technologies | Potential Technologies |
|---|---|---|---|---|---|---|
| | Principal Costs | | Improvements sought | Near Global Coverage | | |
| VARIABLES/TECHNOLOGIES | Capital | Recurrent | | | | |
| Air-Sea Carbon Fluxes | | | | | | |
| $pCO_2$ on VOS (B-1, D-1) | | X | X | | | |
| Automated $pCO_2$ on VOS | | | | | X | |
| $pCO_2$ on drifters | | | | | X | |
| $^{13}C/^{12}C$ ratio | | X | X | | | |
| Ocean color satellite | X | | | X | | |
| Carbon transports and inventories | | | | | | |
| Total $CO_2$ | | X | | | | |
| Tracers | | X | | | | |
| Communications | | | | | | |
| Global satellite comm. Argos (low band) | | X | | | | |
| 2-way global satellite comm. (high band) | | | | | | X |
| Acoustic modem | | | | | | |
| high baud, short range | | X | | | | |
| low baud, long range | | | | | | X |

### VII.B.3. Summary of technologies

The table contains categories for existing, developing, and potential technologies that are, or might be, used to measure ocean climate variables or quantifiable aspects of the climate system. For existing technologies an attempt was made to identify cost attributes, whether improvements are sought, and coverage. The principal costs for using the method/tool considered are identified as capital or recurrent. Significant cost savings might be achieved through mass production for those technologies with high recurrent costs. Indication has been made that improvements are sought in cases where developments are ongoing, shortcomings are clear, or where there are problems with the interpretation of the measurement made (e.g., measurements that do not directly measure the variable of interest) and so may require extensive "calibration" to the specific sites where they are deployed. This table is no doubt incomplete, but represents an initial attempt to identify technological areas of great potential benefit for the ocean observing system for climate.

### VII.B.4. The development process

Technology to be used for an observing system has to meet criteria for low cost, long life, reliability, and ease of manufacture that may exceed the requirements for many research applications. However, there is no better route to the initial development of the needed tools than within scientifically-driven research programs. Once a tool has proven its research capabilities it can then be transitioned to operational use. However, the implementation of a cost effective system also will require focused technology development, because only limited resources are available within present research programs, and the technology requirements will not be identical. We envision two major pathways for technology development related to the observing system:

1. Development within research programs, in which science-directed research programs act as the seed bed for new tools. Those programs which require observing system measurements (e.g., CLIVAR) would be of greatest relevance. Two steps to the process are envisioned. First, an initial emphasis on assuring the quality and stability of the measurements, taking care that accuracy requirements are met within a research program. Second, once a tool has proven its research value, consideration is given for its transition to operational status within the observing system. This would entail evaluation of cost, ease of manufacture and reliability, as well as the potential benefit.

2. Specialized development funded within the observing system. Two types of development projects should be employed. First, projects to address measurement problems for which there is no satisfactory solution at present. Such projects would focus on high priority, unsolved measurement or data telemetry problems. Second, projects to transition a proven measurement system to the high-volume, low-cost manufacturing mode that will be most effective for the system. Here, new tools are given extensive testing, within expanded research programs or the observing system itself. Where overlap exists between an existing observing system element and a new element, they are operated in parallel for as long as practical, to assure continuity and quality of the measurement.

At all stages of these two processes, strong scientific oversight must be maintained to assure that the limited resources available to the observing system are effectively allocated. This would be accomplished by the appropriate oversight within the system. The system management, in conjunction with the funding agencies of participating nations, should have the responsibility for supporting the development process and exploiting the potential of new tools to further the aims of the ocean observing system for climate.

## VII.C. Tradeoffs Between Alternative Sampling Strategies

We should not expect to be able to specify a complete ocean observing system at this time, based on present knowledge and technologies. The observing system must be a continually evolving system. It must be built upon existing technology but must anticipate and encourage the development of improved and new technologies. It must be established on the current base of scientific knowledge; however, it must encourage ongoing, planned and future scientific programs aimed at better describing and understanding the mechanisms of climate change. And, it must be capable of benefiting from the new information gained as a result of these programs.

In designing the observing system, it is essential that we realize there are strategic tradeoffs between competing modes of observing many of the ocean components. These alternative sampling strategies must be delineated and examined now—in the planning phase. And, the observing system must be structured so that it will re-examine these tradeoffs on a continuing basis to take advantage of new knowledge and technology. The continuing examinations are J-GOOS functions (see Section VII.D).

Examples of tradeoffs between distinct observing modes are offered here: different approaches to observations of meridional ocean heat flux and to wind stress monitoring.

<u>Meridional ocean heat flux and flux divergence.</u> Knowledge of the large-scale fluxes of heat between atmosphere and ocean and of heat within the ocean are crucial to global climate studies. Intra-ocean heat fluxes might be used to determine air-sea heat flux. It has been generally agreed that the air-sea heat flux cannot be estimated from a combination of in situ and remote measurements as accurately as is required. The present approach is to estimate across an ocean basin at some given latitude the Ekman heat transport, boundary current heat transports, and interior ocean heat transports separately. The estimates of interior heat flux are obtained from the baroclinic velocity and temperature structure along zonal sections. Estimates made for several, distinct "adjacent" latitude circles may be used to estimate the divergence of heat flux from the ocean. It is thought that the heat flux divergence can be determined from oceanographic data with errors approaching 10 $W/m^2$ (the required accuracy), if data for adjacent latitude circles are acquired over relatively short time periods (say one year). Using traditional ocean data, this is an expensive and time-consuming approach, and likely will be done infrequently. Alternatives are to use new technologies (e.g., the FHP or Slocum and expendable moorings) to collect the ocean data and to consider the use of operational models assimilating near real time data to obtain adequate estimates of air-sea heat flux for the scales required.

For about two decades, extensive XBT measurements of upper ocean heat content have been made from VOS in the mid-latitude North Pacific. Recent studies of these data (TWXXPPC, 1993) indicate that in mid-latitudes on annual to longer time scales it is feasible to estimate net ocean-to-atmosphere heat flux and resolve the expected intradecadal signals to 5 $W/m^2$. This may lead to an alternative approach for estimating air-sea heat fluxes of annual and longer scales.

<u>Wind stress monitoring.</u> It is generally agreed that the wind stress field over the oceans is critical for models, but how should it be observed or estimated? For some years high expectations have been accorded to the use of satellite-based scatterometers for estimating global surface wind fields. This requires both a continuing series of scatterometer satellite missions and selected in situ data. However, it might be possible to average results from operational atmospheric models to obtain monthly averages adequate for detection, study, and modeling on climate scales, if the planetary boundary layer algorithms in such models can be "developed" to correctly represent the atmosphere-ocean wind stress and such results can be verified at selected sites. The ultimate question concerning these tradeoffs might be to decide which ocean measurements, including those from scatterometers, are needed for assimilation into NWP models in order to obtain high-quality wind stress fields.

## VII.D. GOOS Management

In considering a suitable management system for GOOS, one must acknowledge that some of the measurements needed for the operational system are now being made for research purposes. Such measurements will evolve from research to operational over many years. Initially there will be much emphasis on system design and scientific evaluation. Consequently, initial implementation may be quite limited. This scientific design is distinct from research in the WCRP, IGBP, and other climate-related programs, although the design and evaluation will depend in no small measure on the results of such programs. Research in support of the observing system is not an end in itself, but rather a necessity to the continued evolution of the observing system design, implementation, and application.

The observing system must include ongoing strategic planning; that is, it must include components that set requirements for the system, monitor performance, define and evaluate research and technical developments for potential improvements, and examine strategic sampling tradeoffs. Although it seems unlikely that these functions can be carried out by a single body or institution, it is clear that these functions must be supported as part of the observing system and carried out coherently.

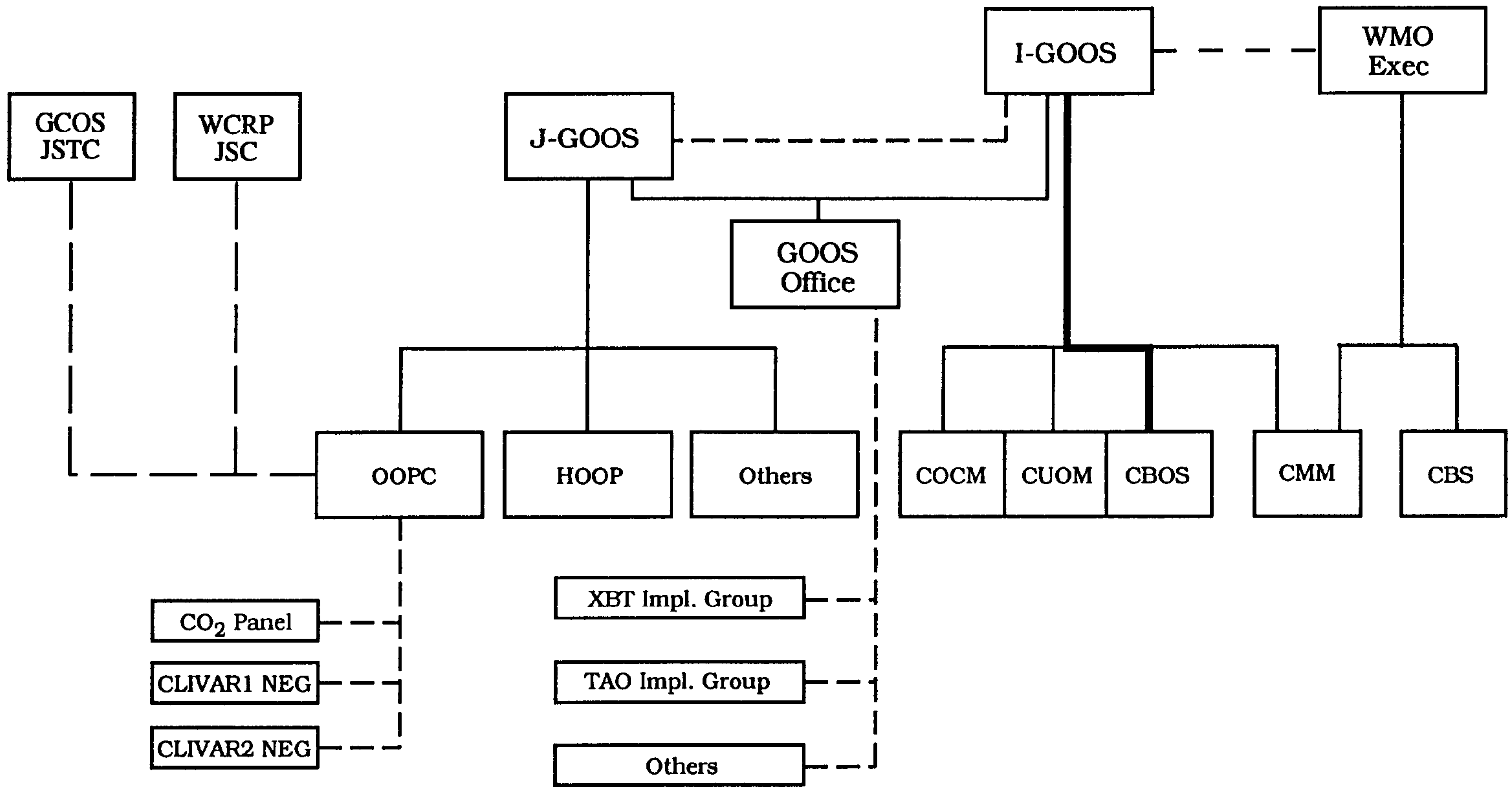
As GOOS matures, implementation and maintenance activities will become the major focus, and design tasks will become minor by comparison. Here we try to describe essential elements of GOOS management and linkages leading to a fully developed GOOS of the future. It seems essential to maintain a long-term view, while realizing that the near-term system will be simpler and differ in focus.

The requirements for the ocean observing system for climate (i.e., goals and subgoals and the required elements needed to meet them) are set by the GOOS and GCOS advisory bodies based on the best scientific and technical advice available. Those same bodies, in cooperation with the JSC of WCRP and the Scientific Committee of IGBP, are responsible for defining and evaluating the impact of research developments on potential system improvements. The measurements required to meet the goals and subgoals of the observing system are achieved through an integrated measurement program (Level I data). The system is compiled by assembly, processing, and quality control of the raw data (Level II data) and analysis and model data assimilation (Level III data). (See Section VI for further discussion.) This is represented schematically in Figure VII.D-1.

The GOOS management responsible for the implementation of the observing system has the added responsibility for evaluating products in an effort to monitor performance. However, GOOS and GCOS are largely comprised of committees of individuals meeting semi-annually or less frequently. They do not have the resources (human or financial) to carry out detailed performance monitoring, assessment of technical developments, examination of strategic sampling tradeoffs, and the like needed to ensure that the observing system is properly operating and evolving to take advantage of new developments without compromising the long data records. We propose a separate unit, called for lack of a better name the "Evaluation Unit", that will have the resources to carry out those functions needed to support GOOS management in the continuing monitoring of performance, evaluation of technical developments, and examination of sampling tradeoffs.

This Evaluation Unit must be designed for tactical response; it must be able to undertake evaluation of the day-to-day system operation relatively rapidly. This unit does not carry out evaluation of the system design; that is the function of the scientific/technical leadership (Joint Scientific and Technical Committee for GOOS (J-GOOS)). Emphasis must be on ensuring that Level II data are flowing at the requisite rates, sampling density, and quality.

This unit must have resources needed to carry out examinations and evaluations as directed by the GOOS management. Although this unit is envisioned as permanent, it need not have a large number of employees. Much of the work could be done by appropriate specialists under contract to this unit. This evaluation unit could be located with the GOOS Office, be located at the site of one of the major centers involved in the assembly and evaluation of the data, or be geographically distributed.




CBOS = Commission for Basic Ocean Systems
CBS = Commission for Basic Systems
CCCM = Commission for Ocean Chemistry Monitoring
CEOS = Committee on Earth Observing Systems
CMM = Commission for Marine Meteorology
CUOM = Commission for Upper Ocean Measurements
HOOP = Health of the Ocean Panel
OOPC = Ocean Observing Panel for Climate

Figure VII.D-1. Schematic relationship of the components of the GOOS, illustrated by those needed for the climate module. GOOS management, together with GCOS management, sets the goals and WCRP advice. The logical progression is from goals and subgoals to defining Level III products. The integrated measurement program leads to level II and finally level III products. Evaluation of the three levels is by GOOS management.

The board of GOOS is the Intergovernmental Committee for GOOS (I-GOOS). I-GOOS interacts with Nations, the IOC, the WMO Executive, etc. The suggested management diagram is shown in Figure VII.D-2. (The proposed management structure shown in Figures VII.D-2 and 3 differs from that proposed by some other groups; it is offered in the spirit of constructive debate.) The J-GOOS is the senior scientific/technical body of GOOS. It formally reports through I-GOOS to Nations, IOC, etc. Based on its own advice and advice from its scientific panels, J-GOOS provides I-GOOS with recommendations to ensure efficiency and correct re-direction of the system. The role of J-GOOS and its panels will evolve as the system matures and changes, from a group of scientists primarily interested in the design of the system, to a group of scientific and technical people whose motivation is provided by operational activities. I-GOOS and J-GOOS are comprised of individuals who meet regularly (but not often) to provide advice and direction. The GOOS Office is a permanent staff that supports I-GOOS and J-GOOS by carrying out the day-to-day management functions on behalf of these Committees.

Directly beneath I-GOOS are the various Commissions which implement and operate GOOS. Borrowing from the WMO organization, there should be one commission with a greater degree of responsibility for overall coordination—equivalent to WMO's Commission for Basic Systems. We have called this the Commission for Basin Ocean Systems (CBOS). The Commission for Marine Meteorology (CMM) would be shared with WMO. Other new commissions would be established as necessary, although great effort should be made to minimize the number of panels and commissions. They likely would focus on basic elements such as the upper ocean, interior ocean, carbon cycle, etc. in such a way as to minimize duplication and maximize effectiveness. For the ocean observing system component, we have shown Commissions for global Ocean Chemistry Monitoring (COCM) and for Upper Ocean Measurements (CUOM). These commissions would in turn create, or make formal connections to, specialist implementation groups, say for XBTs (the present ship of opportunity program (SOOP)), or for TAO measurements in the Pacific. GLOSS, data buoy and other panels would fit in here. Close connections must be maintained on this implementation side of GOOS's house with GCOS and WMO.

The J-GOOS provides scientific and technical design oversight and advice. J-GOOS might be considered analogous to the Joint Scientific Committee of WCRP which has responsibility to executives of its cosponsors WMO, IOC and ICSU. As stated J-GOOS could report to I-GOOS but it would also possess a measure of scientific independence. It should also be linked to GCOS and to WCRP. This would establish clearly the links of GOOS to climate research and broader climate monitoring.

J-GOOS should have scientific expert panels, like the present OOSDP, to continue planning and refinement of the GOOS modules. Shown in Figure VII.D-2 specifically are the Ocean Observation Panel for Climate (planned successor to OOSDP) and the panel responsible for the Health of the Ocean module. It is suggested that the successor to OOSDP be appointed jointly by J-GOOS, GCOS JSTC and WCRP JSC.

In Figure VII.D-3 the functions of the various GOOS bodies related to the ocean observing system for climate are summarized.

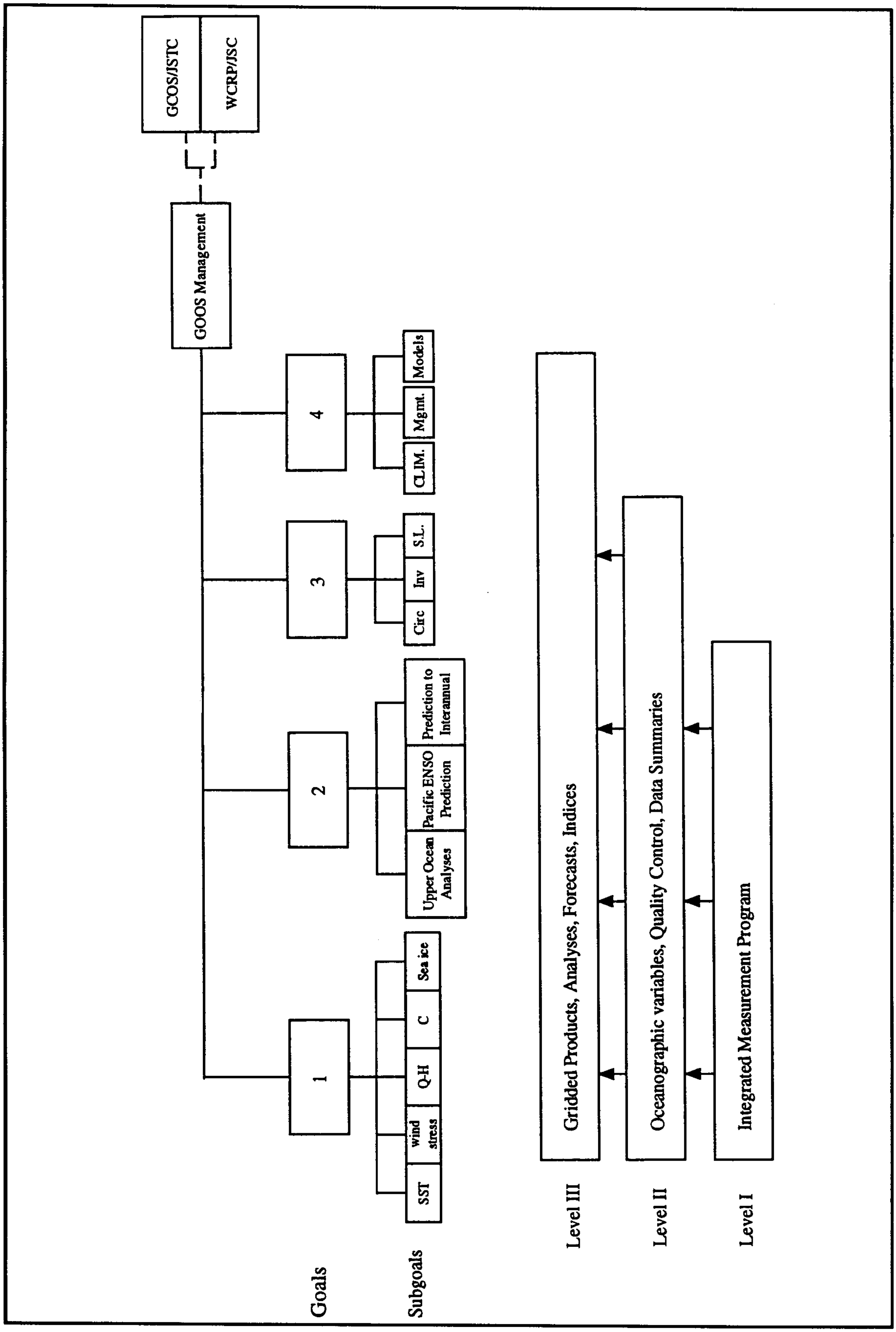



Figure. VII.D-2. Suggested structure of GOOS Management. Relationship to WMO is indicated schematically.

| Function | International Committees | Panels & Commissions | Operational Units |
|---|---|---|---|
| System direction & oversight of implementation (the Board) | I-GOOS | | |
| Countinuing oversight and evaluation of design | J-GOOS | OOPC, HOOP, others | |
| Staff support for design/implementation | | | GOOS Office |
| Implementation of specific platforms/observations | | Commissions | Implementation Units within Nations Data/Model Centers |
| Scientific evaluation of system components | | CLIVAR NEG, WOCE NEG, $CO_2$ Panel, etc. | |
| Operational system self evaluation (Tactical Response) | | | Evaluation Unit |

Figure VII.D-3. Summary of GOOS bodies related to the climate module and their functions.

# VIII. SYSTEM INTEGRATION; SYNTHESIS

Section III.B presented a set of goals and subgoals appropriate for the design of the ocean observing system for climate. Then, in Sections IV and V, the Panel provided information regarding the various components of the ocean climate system, their scales of variability, and suggested suites of observations required for proper temporal and spatial sampling. Focus was on description of air-sea exchanges, interocean fluxes, and storage of heat, fresh water, and carbon. It is now appropriate to return our focus toward the goals and subgoals of the observing system design and provide judgment on the best mix of techniques for meeting these goals.

The first stage of this synthesis is to gather together by subgoals the relevant observing elements discussed in Sections IV and V and factor in the considerations outlined in Sections III (System Design) and VII (System Organization and Evolution). In Section VIII.A.1, we consider the totality of subgoals to which each element and observation would contribute. This provides evidence that some elements, while not of highest priority to any specific goal, may contribute in some measure to attaining a large number of subgoals. Such elements may also be assigned high priority for the observing system.

In Section VIII.A.2, we reverse the procedure of Section VIII.A.1 and consider how well the observing system design presented here meets each subgoal. Each observing element is considered with regard to the recommended characteristics of the observing system measurements presented in Section III.C and its importance in meeting the subgoal. This provides a rough prioritization of elements needed for each subgoal. We also attempt to identify the deficiencies, if any, of the system for attaining each subgoal.

Then, in Section VIII.B.1, we consider which subgoals are more important and feasible to obtain using today's technologies and knowledge. This is an assessment based on consideration of all the information in the previous section, VIII.A. In Section VIII.B.2, we identify the elements of the initial observing system that contribute to the subgoals. Considering those subgoals of higher priority first, enables us to assess the contribution of higher order observational elements to lower order subgoals, and thus, determine the marginal observations needed to attain each subgoal.

In Section VIII.B.3, requirements are reviewed for the self evaluation unit for the ocean observing system for climate. This evaluation unit must be considered as essential to the delivery and archiving of observations required for the observing system.

We complete this section by considering in VIII.C some of the key activities needed to complete the conceptual design, and reality, of the ocean observing system for climate. These include a climate assessment activity, model development and validation, and numerical ocean prediction.

## VIII.A. Observing System Elements Versus Subgoals

### VIII.A.1 Contributions of elements to subgoals (cross-cutting)

Here we consider each of the elements, but not research and development activities, recommended in Section V as part of the observing system in relationship to the subgoals. Table VIII.A.1-1 indicates all subgoals to which each of the recommended elements/observations contributes. The elements are grouped according to the climate variables discussed in Section V.

Note that some measurement techniques may appear on more than one row in this table. This is because they are recommended measurements of more than one climate variable.

# VIII. SYSTEM INTEGRATION; SYNTHESIS

Table VIII.A.1-1. Part 1 of 2.

| ELEMENTS / SUBGOALS | 1a | 1b | 1c | 1d | 1e | 2a | 2b | 2c | 3a | 3b | 3c |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SST | | | | | | | | | | | |
| AVHRR/ATSR | X | X | X | X | | X | X | X | X | X | |
| existing VOS measurements | X | X | X | X | | X | X | X | X | X | |
| VOS improved measurement | X | X | X | X | | X | X | X | X | X | |
| existing surface drifter coverage | X | X | X | X | | X | X | X | X | X | |
| surface drifters in data sparse areas | X | X | X | X | | X | X | X | X | X | |
| TAO array in Pacific | X | X | | | | | X | | | | |
| SSS | | | | | | | | | | | |
| VOS salinograph | X | | | | | X | | | X | X | |
| TAO array | X | | | | | | X | | | | |
| surface drifters | X | | | | | X | | | X | X | |
| Surface winds | | | | | | | | | | | |
| NWP analyses | | X | X | X | | X | X | X | | X | |
| VOS observations | | X | X | X | | X | X | X | | X | |
| SLP on drifting buoys (S.O.) | | X | X | X | | X | | X | | X | |
| TAO array in Pacific | | X | X | | | | X | | | | |
| scatterometer system | | X | X | X | | X | X | X | | X | |
| improvements to VOS observations | | X | X | X | | X | X | X | | X | |
| Surface heat and freshwater fluxes | | | | | | | | | | | |
| NWP analyses | | | X | | | | X | | | X | |
| VOS observations | | | X | | | | X | | | X | |
| drifting and moored buoys | | | X | | | | X | | | X | |
| improvements to VOS observations | | | X | | | | X | | | X | |
| verification meas. from buoys | | | X | | | | X | | | X | |
| atmospheric data from satellites | | | X | | | | X | | | X | |
| Heat and freshwater transports and budgets | | | | | | | | | | | |
| XCTDs from VOS | | | | | | X | | | X | X | |
| conductivity in TAO array | | | | | | | X | | | | |
| autonomous profiling floats | | | | | | X | | X | X | X | |
| river discharge rates | | | | | | | | | | X | |
| repeat hydrographic sections | | | | | | | | | X | X | |
| monitoring transports at key straits | | | | | | | | | | X | |

Table VIII.A.1-1. Part 2 of 2.

| ELEMENTS / SUBGOALS | 1a | 1b | 1c | 1d | 1e | 2a | 2b | 2c | 3a | 3b | 3c |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Upper Layer temperature, salinity and velocity | | | | | | | | | | | |
| existing operational networks | | | | | | X | | | X | X | |
| VOS XBT network | | | | | | X | X | X | X | X | |
| TAO array in Pacific | | | | | | X | X | | X | X | |
| XBT from research and supply vessels | | | | | | X | | X | X | X | |
| autonomous profiling floats | | | | | | X | | X | X | X | |
| XCTDs from VOS and research vessels | | | | | | X | | X | X | | |
| ADCP from VOS and research vessels | | | | | | | | X | | X | |
| Surface drifters | | | | | | | X | X | | | |
| Sea Level | | | | | | | | | | | |
| subset of global tide gauges w/ long records | | | | | | | | | | | X |
| TOGA tide gauge network | | | | | | | X | | | | |
| geocentrically located subset of GLOSS | | | | | | | | | | | X |
| precise satellite altimetry | | | | | | X | X | X | | X | X |
| marine geoid measurement | | | | | | | X | X | | X | |
| Sea Ice | | | | | | | | | | | |
| extent/concentration from satellites | | | | | X | | | | | X | |
| drifting ice buoy networks | | | | | X | | | | | X | |
| submarine acoustic data | | | | | X | | | | X | X | |
| sea ice velocity from SAR/AVHRR | | | | | X | | | | | X | |
| upward-looking sonar | | | | | X | | | | X | X | |
| Carbon | | | | | | | | | | | |
| $pCO_2$/fluorescence from VOS | | | | X | | | | | | X | |
| satellite ocean color | | | | X | | | | | | X | |
| $pCO_2$ and fluorescence from drifters | | | | X | | | | | | X | |
| time series for carbon components | | | | | | | | | X | | |
| $^{13}C/^{12}C$ from VOS | | | | X | | | | | X | | |
| Total carbon | | | | | | | | | X | X | |
| Circulation and Inventory measures | | | | | | | | | | | |
| time series (sections/stations for monitoring deep/bottom water renewal) | | | | | | X | | | X | X | |
| compile velocity data | | | | | | | | | | X | |
| transocean sections | | | | X | | | | | X | X | |
| improved bathymetry | | | | | | | | | | X | |

Consideration of the number of subgoals to which an element contributes may provide one measure of overall priority for that element within the observing system. Of course, that measure of priority is not the only consideration. It must be weighed against the feasibility of attaining the goals. A certain element may be essential to meeting a specific subgoal, in terms of contributing high impact while being feasible, yet not be useful for attaining other subgoals.

### VIII.A.2 Feasibility of observations and impact to individual subgoals

In assigning priority to the contribution of specific observational elements to specific design subgoals, there are several issues that are relevant, not all of which can be fully covered within the terms of reference of the OOSDP.

Scientific impact. This report has detailed the current state of scientific knowledge in regard to the various components of the climate system and provided scientific justification for the application of various measurement and analysis techniques. The issue now is the relative impact of these contributions to the scientific subgoals. This subjective evaluation is referred to here as the scientific *impact.*

Operational issues. Section III.C presented a set of required characteristics for measurements for the ocean observing system for climate. These have been effectively adopted by GOOS as the definition of an operational measurement (IOC, 1993). By way of review these characteristics are: long term, systematic, relevant to the global climate system, subject to continuing examination, routine, timely, and cost effective. The long-term and relevance characteristics are not at issue. It is assumed that all recommended measurements will be continued indefinitely—or until replaced by a better measure/technique. The issue of relevance to the global climate system is key to the assignment of *impact.*

The other main considerations are that the measurements (and analysis and management systems) should be routine, systematic, cost effective, timely, and subject to continuing examination. This report is effectively the first stage in the continuing examination of the observing system. There is no objective measure available for assessing how well particular elements satisfy these criteria but it is clear that the degree to which this is achieved is a central issue for the system design. The Panel has adopted a subjective assessment which we term *feasibility* as a relative appraisal of the extent to which an element satisfies these characteristics. Implicit in this judgment is some unspecified weighting between the routine, systematic, timely, and cost-effectiveness characteristics. The latter factor is not treated in any precise way. It may be important in some cases to evaluate the relative contributions of these factors to the *feasibility*, as well as considerations like robustness and accuracy.

Economic cost. The costs of the observing system and its elements must be taken into account as the system is implemented. However, it is beyond the scope of this Panel to do this in a methodical and credible fashion. This task is left to implementation committees and panels.

Benefits. Section I.B presented some example and potential applications of the observing system and their benefits. This report does not provide detailed quantitative evaluations of the existing and potential economic benefits of implementing an observing system, although it is clear that this must be done to provide the rationale for financial support of the system. Other planners of the GOOS and GCOS are proceeding with such evaluations. There is some measure of actual benefit implicit in the choice of subgoals (they are chosen because they were perceived to be useful), and the *impact* is in part a measure of the contributed benefit. Ultimately the judgment on actual economic cost and benefit will be made by those responsible for implementation, but it is the Panel's belief that the assessment of *feasibility* and *impact* made here will make a significant contribution to this judgment.

In the following we attempt to summarize the conclusions of the previous sections with schematic diagrams of *impact* versus *feasibility* for each of the subgoals. It must be accepted that these schematics are not the total picture and sometimes over simplify the realities of taking observations or delivering products. Nevertheless the Panel felt it is important to make these deliberations as explicit as possible, rather than rely on the reader to integrate the various details presented throughout this report. The schematics are supplemented with contextual information as required.

There is considerable overlap between the elements of the observing system recommended for the various subgoals. The *impact* and *feasibility* assigned to an element needed for one subgoal may not match those assigned the same element for another subgoal. *The schematic summaries make no attempt to represent the relative importance of each subgoal, so caution must be exercised when comparing judgments across subgoals.*

For both the *impact* and *feasibility* a low, medium, or high weighting is assigned to each element taking into account the considerations above. Note the implication that the measure is relative and not absolute. A crude prioritization can be estimated by summing these ratings, though no attempt is made here to assign relative weighting to the *impact* and *feasibility*. The observational elements are shown as measurements or estimates needed; platforms/tools are indicated as appropriate—if more than one option is available. No attempt is made to show interdependencies, for example of one measurement on another or efficiencies gained through multi-functioned platforms (though it is factored into the *feasibility* to some degree).

On the feasibility-impact diagrams, Figures VIII.A.2-1 to 11, the required elements are classified as belonging to one of three categories using color coding. They are the same categories as have been used in Section V in formulating the recommendations for the required elements for the ocean observing system for climate, except that in Section V an additional research and development category is also used. Following the definitions given in Section V, the categories are:

Category 1: Elements of existing "operational" systems, which are shown in black.

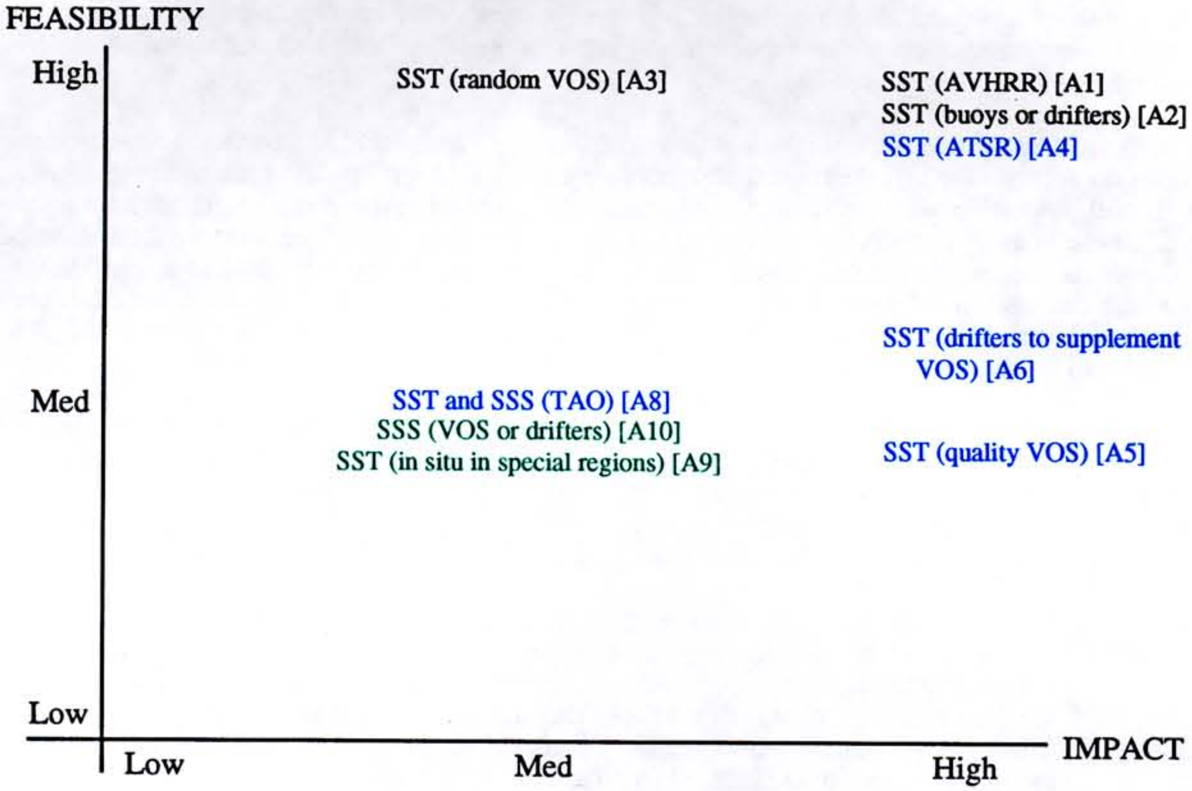
Category 2: Elements to be added now to complete the initial observing system—either enhancements to existing operational systems or parts of existing research observing systems ready for conversion to operational status, which are shown in blue.

Category 3: Elements, perhaps not now readily obtainable, urgently required as enhancements to the initial system at the earliest feasible time, which are shown in green.

On some of the feasibility-impact diagrams for some subgoals, climate variables that are provided by another subgoal are shown in purple. For such subgoals, the required observational elements include both those indicated specifically on the feasibility-impact diagrams and those required for the climate variables indicated in purple.

After each element on the feasibility-impact diagrams is an indication in [ ] either of the location and number of the recommendation(s) of that element in Section V (e.g., [A4] refers to recommendation 4 in Section V.A) or of another subgoal that will contribute that element.

Figure VIII.A.2-1. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 1a: To provide in situ measurements of SST that, when combined with satellite measurements, are adequate for defining SST field variability on monthly, seasonal, interannual, and longer time scales. Where it can be determined with sufficient accuracy, sea surface salinity and its variability should be measured.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

SST is a variable for which a product now exists and this has guided the OOSDP recommendations.

<u>The minimum set of requirements</u> are:

- existing operational measurements now contributing to SST products (AVHRR with in situ SST from VOS and buoys);
- SST from ATSR;
- SST from a subset of VOS with improved sensors;
- SST from drifters in data sparse regions; and
- conductivity and SST from selected moorings.

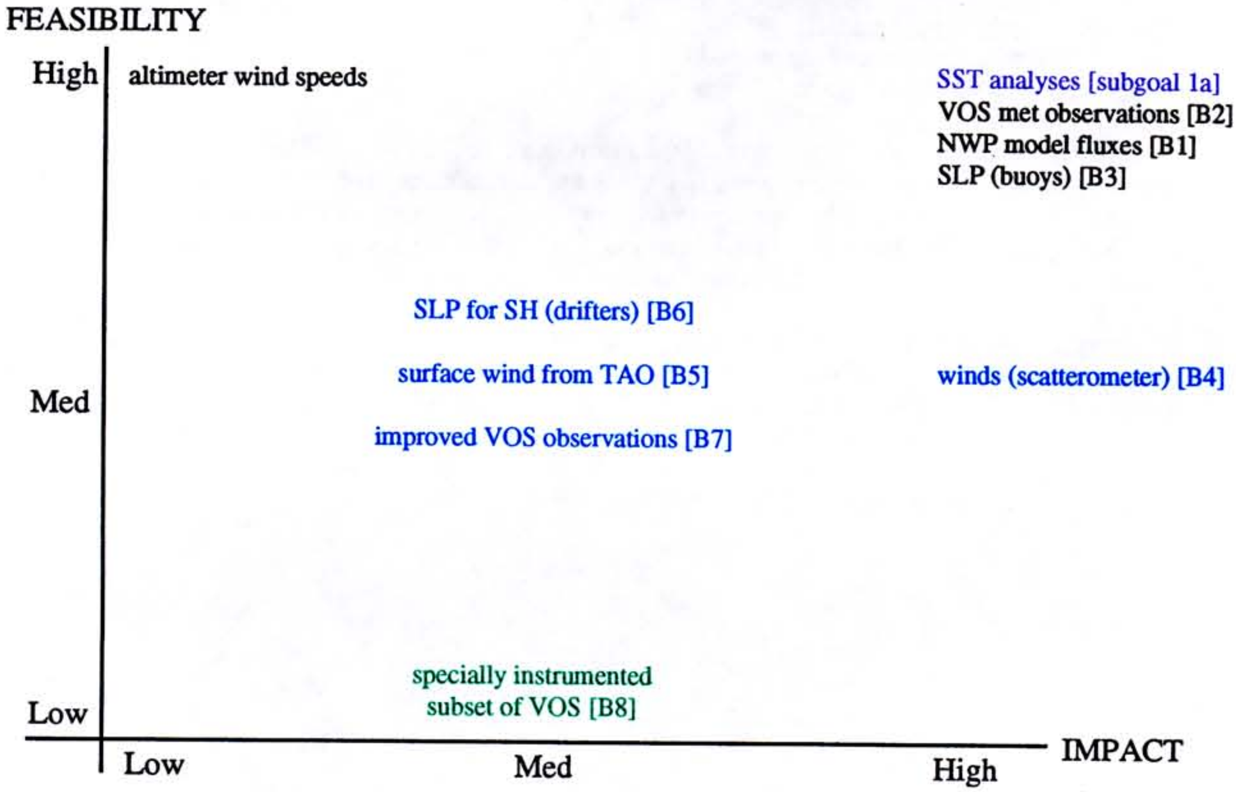
At present, SST is obtained using AVHRR measurements from space combined with in situ SST from standard VOS and from drifting and moored buoys. The buoy data, because of their accuracy, have the most impact on the calibration of the AVHRR data. Included in the buoy data set are the SST data from the TAO array. The initial system needs the addition of further observations for calibration. This includes measurements of SST from drifters in data sparse regions, such as the Southern Ocean, and from a subset of VOS fleet equipped with improved (hull contact) temperature sensors. ATSR SST should be used to establish transmission errors in satellite SST data. Limited SSS observations are now available from some buoys, including the TAO array. This coverage should be increased. It should be noted that information from sea ice analyses (subgoal 1e) is used in SST analyses, although that is not shown in the diagram.

The system would be improved by:
- SST observations in special regions and
- SSS observations from VOS and drifters.

In certain regions, satellite SST observations are inadequate because of cloud cover or other problems and increased in situ observations are required to provide sufficient accuracy and resolution. Although global SSS coverage is not feasible at present, the development of the operational use of thermosalinographs on VOS and conductivity sensors on drifters could provide critical data. On the longer term, improvements need to be sought in both in situ measurements and those from space, perhaps including SSS.

Deficiencies. The lack of satellite data relay capability now limits the volume of data that can be retrieved from surface buoys and ships, and thus the number of such platforms that can usefully be deployed. This, together with limitations in our ability to take in account differences between skin temperatures observed by satellite and in situ observations, limit our ability to define the SST field. The lack of operational thermosalinographs, affordable, proven salinity sensors for buoys, and a remote sensing capability for salinity limits our ability to obtain global SSS observations.

Figure VIII.A.2-2. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 1b: To assist in providing data at the sea surface and in the marine boundary layer needed to estimate global distributions of the surface flux of momentum (wind stress) on monthly, seasonal, interannual, and decadal time scales.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

The only global wind or wind stress products presently available are those derived from NWP analysis. Even if a proven operational scatterometer becomes available, NWP analyses and the observations they assimilate will continue to play a major role in defining the ocean observing system for wind stress.

<u>The minimum set of requirements</u> are:

- existing surface meteorological observations from VOS and buoys and NWP analyses;
- an operational satellite scatterometer;
- SLP from Southern Ocean drifters;
- surface wind from TAO; and
- improved VOS observations.

At present estimates of the large-scale surface wind are primarily obtained from the analyses of NWP models that assimilate a variety of ocean data which have high impact. These include SST analyses, VOS meteorological observations and buoy data. Scatterometer data have the potential for providing the wind stress, and data for assimilation into models; however an operational scatterometer system has yet to be implemented.

There is also a requirement for more and improved in situ observations. In particular, drifter SLP is needed in the Southern Ocean for input to NWP models, and direct wind observations from the TAO array are required for ENSO prediction. It also is feasible to improve VOS observations through changes in procedures. Measurements are needed for calibration of satellite observations and these may be obtained from moored arrays (see also subgoal 1c). It should be noted that information from sea ice analyses (subgoal 1e) is used in preparing global air-sea flux estimates, although that is not shown in the diagram.

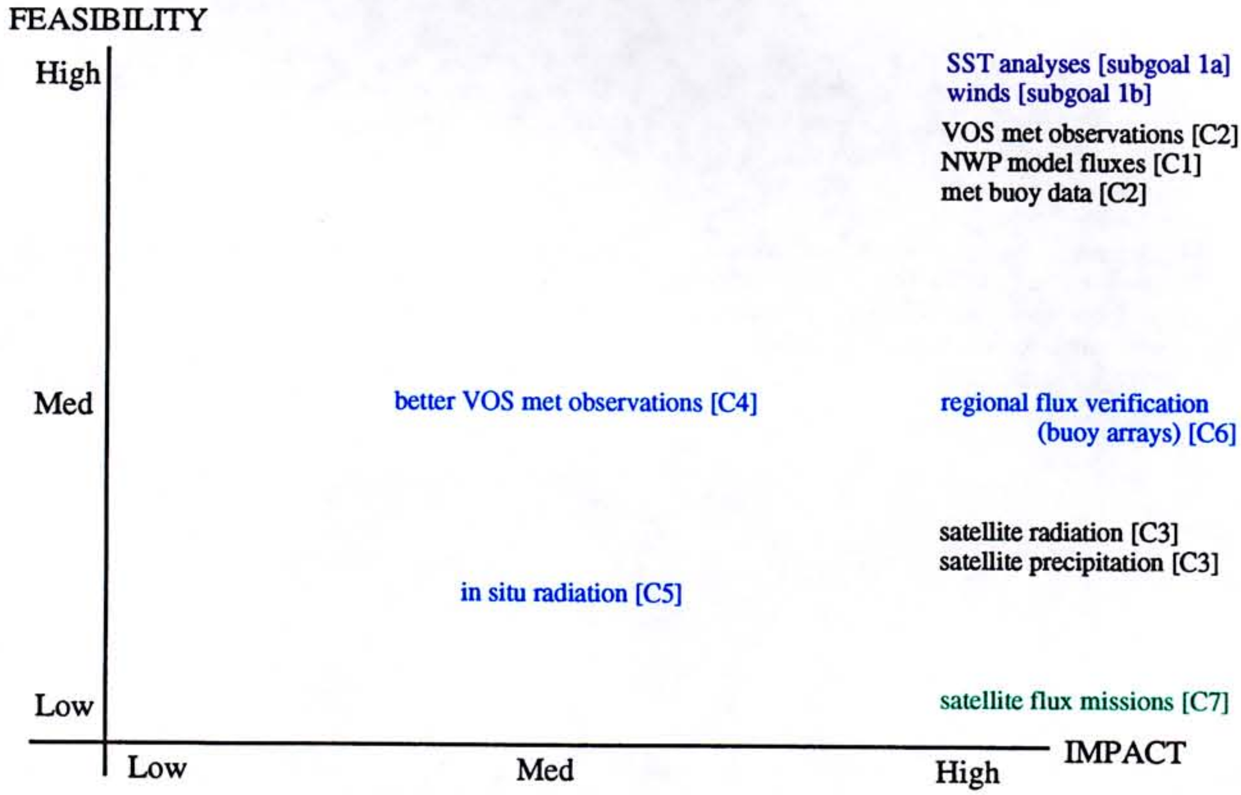
The system would be improved by:

- improved wind measurements on a subset of VOS.

Depending on the success of an operational scatterometer wind system, consideration should be given to improvement of wind measurements on a subset of VOS using better automated systems. Wind stress might be obtained using the inertial dissipation technique. Satellite wind speed products from radar altimeters or passive microwave radiometers may also be used, but the first is limited by restricted spatial coverage and the second by accuracy.

Deficiencies. Present NWP models produce wind fields that differ from one another, especially in data sparse regions. Reliance in the future on such fields will require efforts to improve both the availability on a global basis of in situ winds and the performance of the models. Use of satellites to fulfill subgoal 1b requires a commitment to operational deployments of such satellites with orbits chosen to provide reasonable global coverage and continued efforts to improve satellite algorithms for determining wind and wind stress.

Figure VIII.A.2-3. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 1c: To assist in providing data at the sea surface and in the marine boundary layer needed to estimate global distributions of the surface fluxes of heat and fresh water on monthly, seasonal, interannual, and decadal time scales. Additional constraints on these estimates will be provided by estimates from upper ocean budgets.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

*For the determination of heat and water fluxes the only feasible approach is to use the fields produced by NWP* models in conjunction with in situ and satellite observations. Thus, the elements of the ocean observing system for climate for air-sea fluxes (sensible and latent heat, radiation, and precipitation) have been defined as follow.

The minimum set of measurements are:

- existing NWP surface flux analyses and the existing VOS, buoy, and satellite-based observations in their support;
- improved meteorological observations from VOS;
- in situ radiation observation on VOS; and
- regional flux verification arrays.

Given the role of NWP models in the determination of surface fluxes, priority has to be given to critical observations for assimilation into them and for verification and improvement of the algorithms used in their codes. Such data have high impact; they include SST analyses and VOS meteorological observations that include surface radiation and precipitation and are of improved accuracies. Satellite precipitation and radiation estimates would also have high impact if the required accuracy can be obtained. There is a requirement for data to verify model flux determinations. The latter include quality surface observations from VOS and buoy arrays designed for flux verification. The improved VOS observations are possibly more feasible; however, the buoy data would be expected to be more accurate and therefore of higher impact. It should be noted that information from sea ice analyses (subgoal 1e) is used in preparing global air-sea flux estimates, although that is not shown in the diagram.

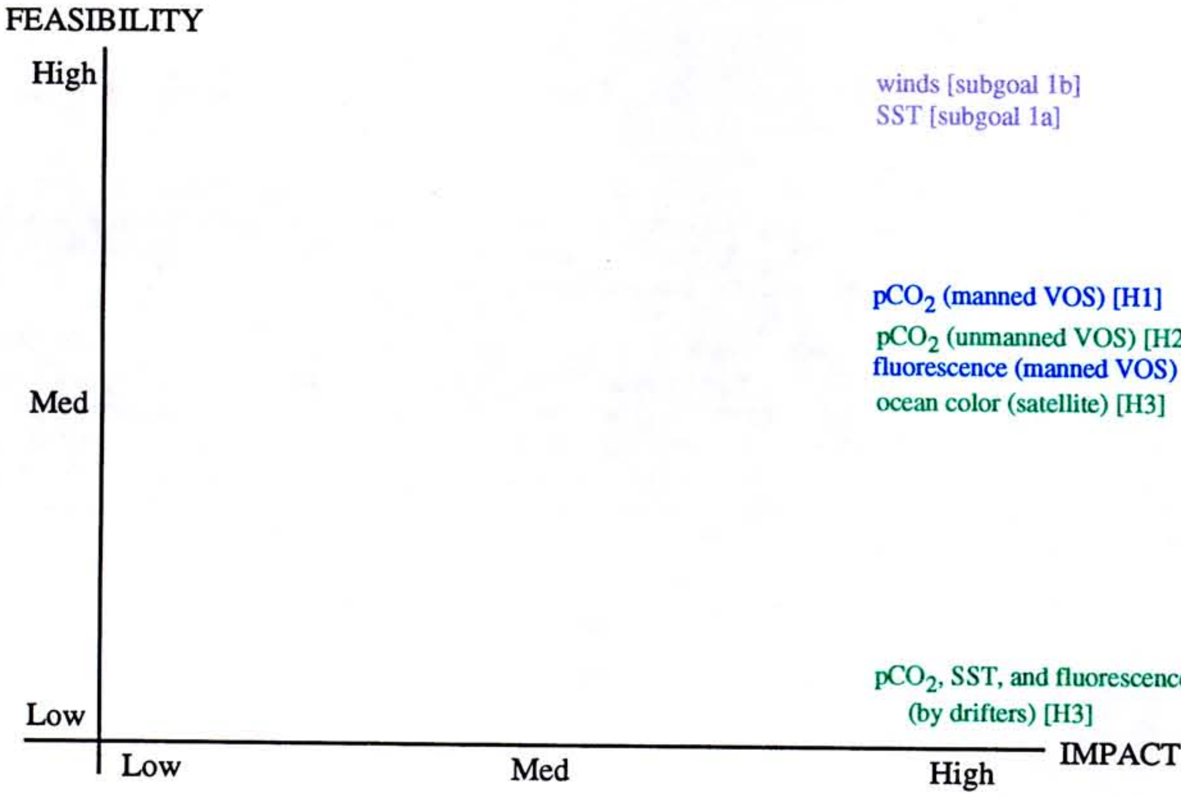
The system would be improved by:

- operational satellite measurements for ocean surface flux determination.

There is a need to define operational satellite measurements for ocean surface flux determination, making remotely-sensed radiation and precipitation fields, calibrated with in situ data, available in a timely manner similar to present SST products. These are expected to place emphasis on determining surface insolation, wind velocity and precipitation. Consideration should also be given to the long-term determination of direct flux observations, including precipitation, from a variety of platforms. Improved surface flux determination depends on improved satellite observations, the effective assimilation of both in situ and satellite-based observations in NWP models, and the existence of direct flux measurements for flux verification.

Deficiencies. The challenge of obtaining surface heat and freshwater fluxes on a global basis is significant. NWP models are limited by their need for computational efficiency in how sophisticated their parameterizations of clouds can be. This in turn limits their ability to predict radiative fluxes and freshwater flux at the sea surface. Satellites provide radiation at the top of the atmosphere. Satellite surface radiation estimates, like other heat flux related measurements, are limited by the difficulties related to the ability to resolve the vertical structure of the atmosphere. Operational, in situ, open ocean rain measurements of proven accuracy remain an elusive goal; this limits the efforts to improve satellite sensing of precipitation.

Figure VIII.A.2-4. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 1d: To provide the physical, chemical, and biological data required to describe the global distribution of sources and sinks for atmospheric carbon dioxide and the carbon exchanges within the interior of the ocean. Initially, monthly climatologies of the exchanges are required to resolve longer term changes in the presence of strong variability on interannual and shorter time scales.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

Recent observations of atmospheric $CO_2$ concentration show a decline in the rate of increase for the years 1991 to 1993. Lack of observations prevents us from determining the contribution of ocean processes to this effect. Therefore, one priority for the observing system is to resolve the annual time scale for ocean-atmosphere exchanges of $CO_2$. Although this subgoal focuses on annual time scales and the upper ocean, in the longer term the accumulation of systematic observations of the upper ocean will be compared with changes in the ocean inventory of carbon and its transport by the full depth circulation (subgoals 3a and 3b).

<u>The minimum set of requirements</u> are:

- $pCO_2$ from manned VOS and
- fluorescence from manned VOS.

Initially, the system requires enhancement of the existing research measurements of $pCO_2$ and fluorescence on manned VOS. Where possible the $pCO_2$ measurements should be accompanied by the analysis of the $^{13}C/^{12}C$ ratio of $pCO_2$ in discrete samples. The system requires wind products for calculations of exchange rates in the sampled areas. Global wind and SST products are also needed for extrapolation to the global scale.

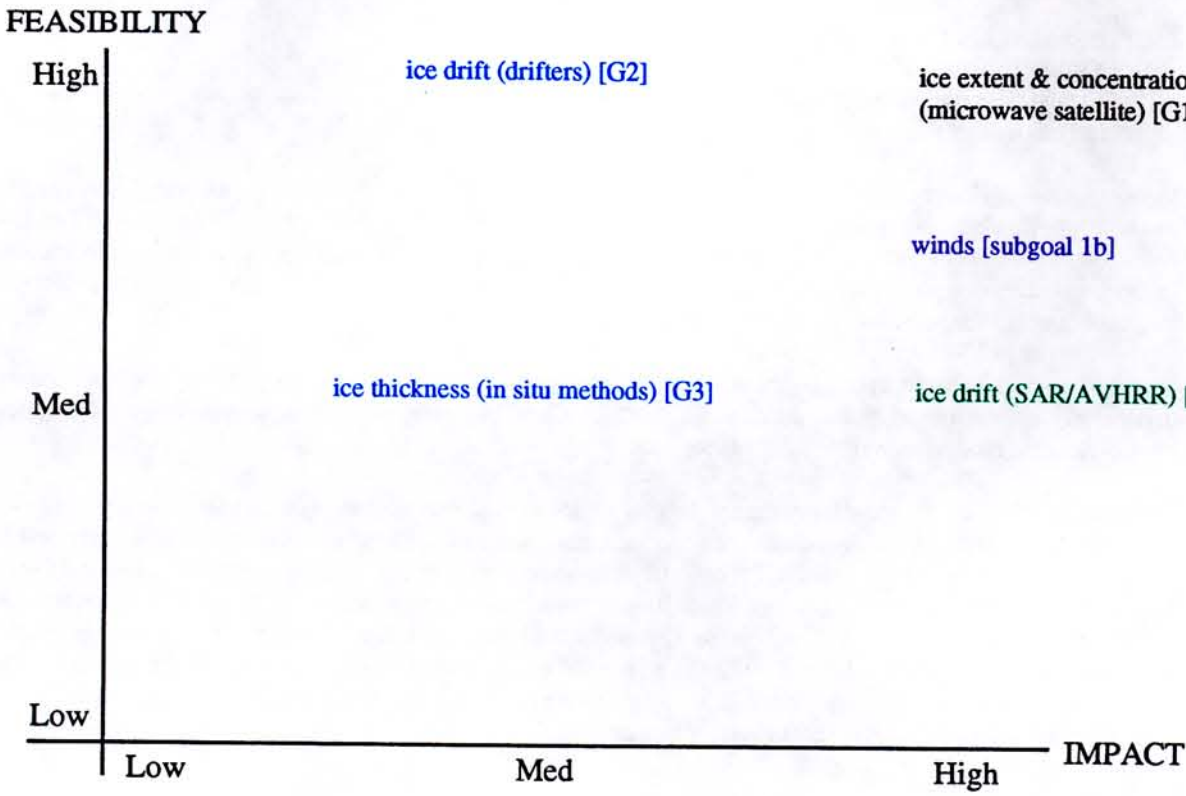
The system would be improved by:
- $pCO_2$ from unmanned VOS;
- $pCO_2$ and fluorescence from drifters; and
- ocean color from satellites.

Measurements of ocean color from research satellites will be available shortly and help provide global coverage of chlorophyll, which is a proxy of the role of the biological pump in absorbing $CO_2$. Ground truth has to be provided first by VOS and then by drifters equipped with $pCO_2$, fluorescence, and SST sensors. In addition, drifters will enhance the space and time coverage of VOS. For the annual time scale, this constitutes the minimum system for resolving fluxes on a global scale.

In the future, this basic system would be considerably improved with the addition of nutrient sensors, particularly nitrate, on VOS and drifters. This would allow large improvements in the design on physical-biogeochemical models as well as their validation.

Deficiencies. The basic system cannot meet the goal to describe carbon exchanges with the ocean interior. There are multiple physical and biogeochemical processes that exchange carbon between the surface layer and the interior ocean. At present, the relative importance of these processes in determining the net flux into the interior and the critical time and space scales at which they operate remain poorly understood. Much more information and syntheses from the JGOFS process experiments and time series will be required before a credible observational strategy can be defined. At the same time, the ocean observing system will require process models that can assimilate both remotely sensed (e.g., ocean color) and in situ biogeochemical data to interpolate fluxes over regional and global scales. This is also a principal goal of JGOFS.

Figure VIII.A.2-5. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 1e: To provide data to describe the extent, concentration, volume, and motion of sea ice on monthly and longer time scales.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

As part of the cryosphere, sea ice is a basic component of the climate system. It forms a barrier between the ocean and atmosphere and its seasonal growth, movement, and decay are important in global exchanges of heat and fresh water. In both the Arctic and Antarctic, sea ice influences the creation of deep water masses. On long time scales, it is thought to be a sensitive indicator of climate change. The emphasis is on developing a long-term climatology of sea ice and its variability that can be used to monitor climate change and to test and validate model simulations.

The minimum set of requirements are:

- global sea-ice extent and concentration estimates from passive and active microwave satellite observations and, in specific regions, from SAR and
- ice drift using tracked drifting buoy networks.

Microwave sensors provide the only all-weather method of obtaining global estimates of sea-ice extent and concentration, but serious problems remain in their interpretation. In clear skies, the average albedo can be estimated from visible channel data or AVHRR imagery. Sea-ice regions vary greatly in character and there is difficulty in establishing algorithms to describe sea-ice concentration in the presence of snow cover, melt water, thin ice, ice of different year classes, etc. Measuring ice velocity using drifting buoys is a proven technique, but existing networks in the Arctic and Antarctic are sparse and regional in spatial coverage.

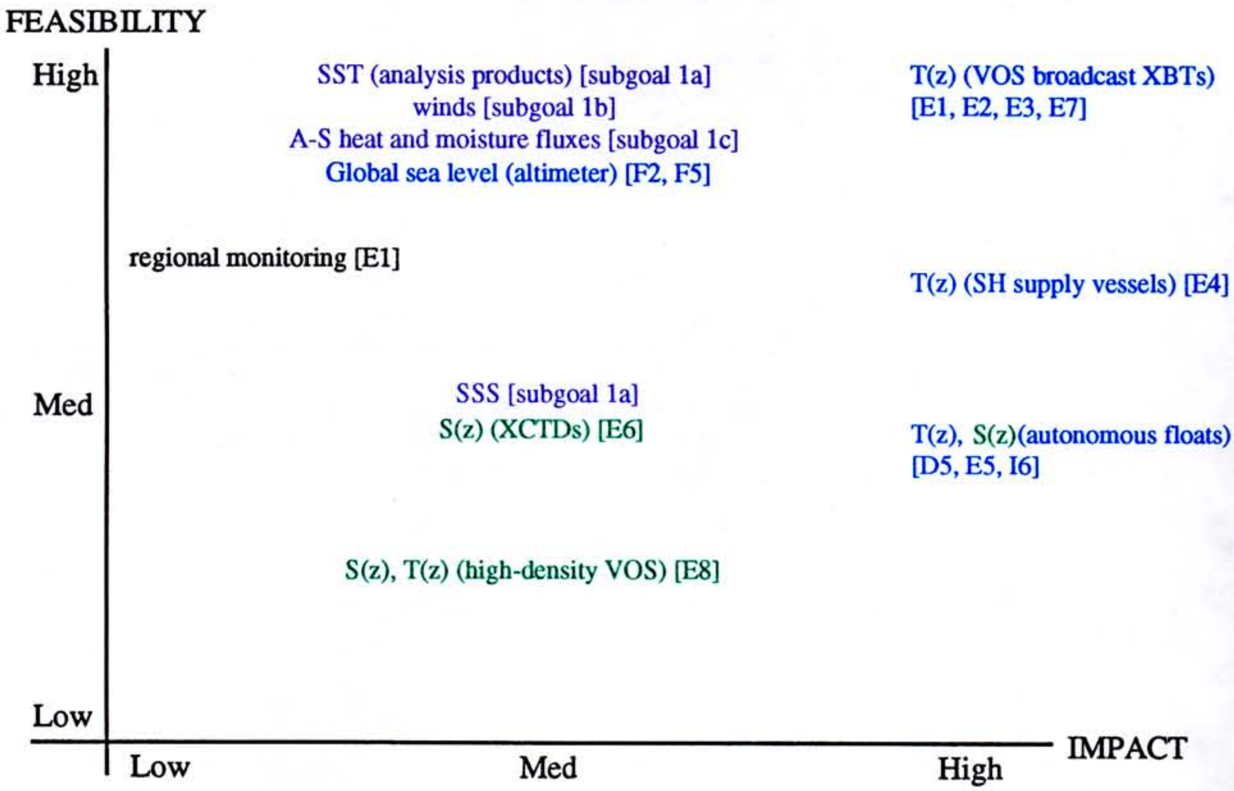
The system would be improved by:

- routine determination of ice drift using SAR and
- upward-looking sonar measurements of ice-thickness from moored arrays.

High spatial resolution fields of ice motion can be obtained from SAR (as on Radarsat) by tracking floes. To routinely obtain large-scale synoptic measurements, the development and application of automatic techniques is required. Measurement of ice-thickness from space does not seem to be feasible. Limited upward-looking sonar measurements have been made in the Arctic both from submarines and research moorings, although much of the former data are not now available. Regional buoy arrays, such as planned for the Arctic under the ACSYS program would provide data to monitor long-term change and to improve and validate sea-ice models.

Deficiencies. The recommended system is deficient in meeting various aspects of subgoal 1e. One serious lack is the existence of any technique to determine ice thickness or volume on global scales. Another is the inability to accurately estimate the fractions of thin ice and open water that are important as regions of intense air-sea heat exchange. Improvement may come from the various research programs which are obtaining local or regional in situ data, which can be used both to improve the algorithms used to interpret satellite data and to develop improved models of ice growth and transport. A goal for the future would be the assimilation of available data in improved coupled ocean-atmosphere-sea-ice models on an operational basis.

Figure VIII.A.2-6. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 2a: To provide global data for monitoring, understanding, and analyzing monthly to interannual upper ocean temperature and salinity variations.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

This subgoal is principally concerned with the determination of low-frequency temperature and salinity changes on spatial scales greater than that of oceanic variability (e.g., mesoscale eddies). It is not concerned with prediction. The observation network recommended here, in conjunction with surface products and upper ocean data gathered for other purposes, aims to provide relentless data collection which, over time, will result in an accurate determination of the mean state and variance of the temperature and salinity fields and of long-term changes in upper ocean storage.

The minimum set of requirements are:

- an upper ocean temperature sampling program, principally using VOS XBTs in broadcast mode, supported wherever possible by opportunistic sampling on research and Antarctic supply vessels;
- wind stress, SST, air-sea heat flux (from subgoals 1a, 1b, and 1c); and
- SSS and/or air-sea freshwater flux, particularly in regions where salinity is known to be critical.

The foundation of the upper ocean observation program will be provided by a broadcast XBT sampling network using VOS; in essence this recommends maintenance of the present research VOS XBT network sampling according to the broadcast mode strategy. There should be a concerted effort to maintain an XBT program on

Antarctic supply vessels as this is one of the few strategies available for collecting data in these regions. At present there are few operable alternatives for obtaining upper ocean temperature other than the use of subsurface autonomous floats (e.g., ALACE) that can obtain temperature, and perhaps salinity, profiles in the global ocean.

For monitoring of low-frequency change it is critical that the surface wind and thermohaline forcing is known. The wind stress is critical for calculating the horizontal flux of heat due to surface Ekman currents. SST (or surface heat flux) is required for the surface thermal boundary condition; present knowledge would suggest SST is the most critical. In some cases, such as in the subpolar gyre of the North Atlantic, it is also critical to monitor upper ocean salinity. In the absence of a viable strategy for sampling upper ocean salinity profiles it is important that every effort is made to determine surface salinity or, if possible, the net surface water flux. Necessary surface fields are provided for by the strategies outlined for subgoals 1a, 1b, and 1c.

<u>The system would be improved by</u>:

- vertical T and S profiles using subsurface floats;
- sea level (altimeter); and
- subsurface salinity (as the opportunity arises).

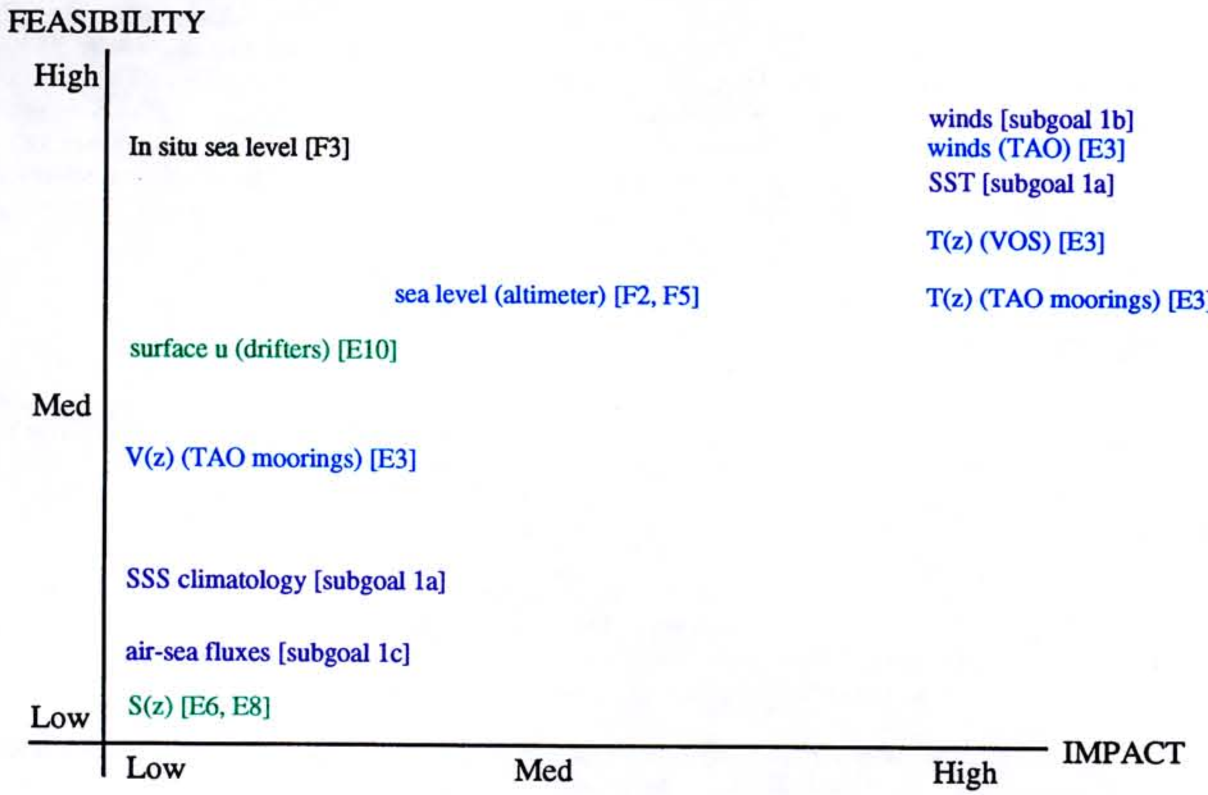
Altimetry offers the possibility for global coverage that is not feasible by other means. It does not directly give any information on temperature or salinity, or on their variation with depth, but it does provide an estimate of their combined, vertically integrated effect, and so would provide valuable additional information on long-term changes in storage and transport, and on the strength of the major gyres.

It is also important that the observing system endeavor to improve our knowledge of the annual salinity cycle, particularly at high-latitudes. This requires continued technological development of the XCTD, but if, as seems likely, this instrument can be produced with the required reliability and accuracy, and at reasonable cost, a subset of the VOS should be used to improve the sampling of upper ocean salinity.

<u>Deficiencies.</u> The most important deficiency of the basic system recommended here is that it does not guarantee global coverage. The lack of salinity measurements can be tolerated; the lack of temperature measurements is a more serious weakness. There is also a strong dependence on surface fields and fluxes. It is not certain that the estimates of the surface fluxes of heat and moisture will be adequate for the purposes here.

In a sense these deficiencies have been acknowledged in the framing of the subgoal; the focus is on large-scale, low-frequency monitoring and analysis. However, the realities of the available technology mean that even this objective is hard to reach. The strategy relies on long periods of sampling to overcome uncertainty due to the lack of temporal and spatial resolution, but the success of this strategy cannot be assured. Depending upon the results of WOCE, it may be desirable to augment the broadcast mode sampling with selected high-density XBT lines. The benefits of a routine, relentless program of data collection will only be realized in the long term, but it is an outcome worth pursuing.

Figure VIII.A.2-7. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 2b: To provide upper ocean data in the tropical Pacific for the initialization and verification of models for ENSO prediction.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

This subgoal has been separated from the more general prediction problem (subgoal 2c) because there is proven feasibility of monitoring and predicting seasonal to interannual variability associated with the ENSO phenomenon.

<u>The minimum set of requirements</u> are:

- wind stress (subgoal 1b);
- SST (subgoal 1a); and
- upper ocean temperature (TAO + VOS + ALACE) [not as high priority as wind and SST].

Knowledge of surface wind stress in the tropical Pacific Ocean has been acknowledged as the most important information element for ENSO prediction. It is used directly in stochastic prediction schemes and indirectly to initialize simple and complex models for analysis and prediction of equatorial Pacific Ocean temperature. SST is the most widely used oceanographic parameter in monitoring interannual variability in the Pacific Ocean and is also used in stochastic and deterministic model predictions.

Upper ocean temperature data have become important in ENSO monitoring and analysis activities, probably more useful than SST alone. There is also mounting evidence that upper ocean data will be critical for improving the skill of ENSO model predictions; the results of TOGA are sufficient to conclude that such data are necessary, but we cannot state that they match the priority of wind stress and SST.

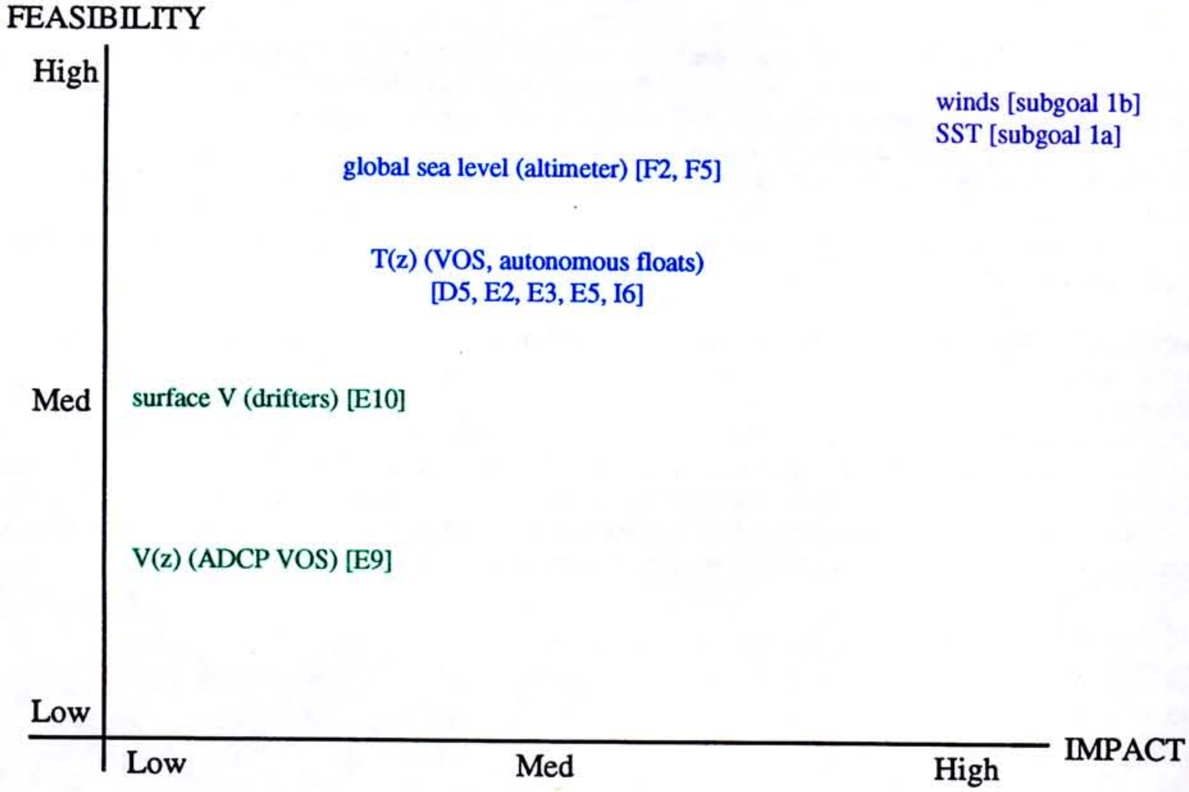
The system would be improved by measurements of:

- sea level (a combination of in situ and altimetry);
- surface currents;
- subsurface currents on a subset of TAO; and
- climatology of SSS (for model boundary conditions).

On available evidence it would seem that the best opportunity for improved prediction skill is through better models and improved model data assimilation. Surface and subsurface current data are required for validation of ocean models and for independent monitoring of heat transports by ocean currents. Sea level provides an indirect measure of the tropical ocean response to wind forcing and ocean heat storage. It has a long history of use as a monitoring tool and is useful for model validation. It can be anticipated that altimeter data also will be useful for model initialization. The majority of ocean models include salinity as a prognostic variable; SSS is required as a surface boundary condition though, at this time, there is insufficient evidence to warrant a campaign for real-time determination of SSS.

Deficiencies. While there is significant research still to be done, it would seem that improvements in ENSO prediction will not be limited by the observation network recommended above; it is necessary and adequate. The limitations are provided by the models used for prediction and, in particular, the limitation of coupled ocean-atmosphere GCMs. The recommended observations will be critical for this model improvement. There is insufficient scientific evidence to recommend real-time collection of salinity data (say, from XCTDs) or ocean current data for initializing prediction models. The latter will be the most useful for validation. On existing evidence there is also not a strong case for surface heat flux or surface moisture flux as boundary conditions for prediction models, though their use as validating fields for models is important.

Figure VIII.A.2-8. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 2c: To provide upper ocean data outside the tropical Pacific for the understanding and description of ocean variability and for the initialization and development of present and future models aimed at climate prediction on seasonal to interannual time scales.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

Here the primary objective is prediction from time scales of weeks out to interannual, ideally for the global domain and spatial scales ranging from regional out to gyre scale. In essence it is the generalization of subgoal 2b to the global domain and to variability over a broader range of time scales. At present such prediction is only feasible on regional scales, and then only if there is a superior data coverage to allow proper initialization. The recommendations recognize the worth of supporting regional "pilot" activities as well as taking a more long-term view for the global problem.

The minimum set of requirements are measurements of:

- global sea level by altimetry;
- wind stress; and
- SST.

It is not clear whether these elements constitute the absolute minimum for a prediction program; insufficient research has been done at present. However, on the basis of available research, it would seem that a combination of altimeter data (as a proxy for thermocline deviations), SST (for surface structure and fine detail), wind stress, and advanced model data assimilation techniques offer the best strategy. The reality is that such a system may not be realizable in the short term. Certainly, altimetry seems to offer the only practical alternative for understanding mesoscale variability.

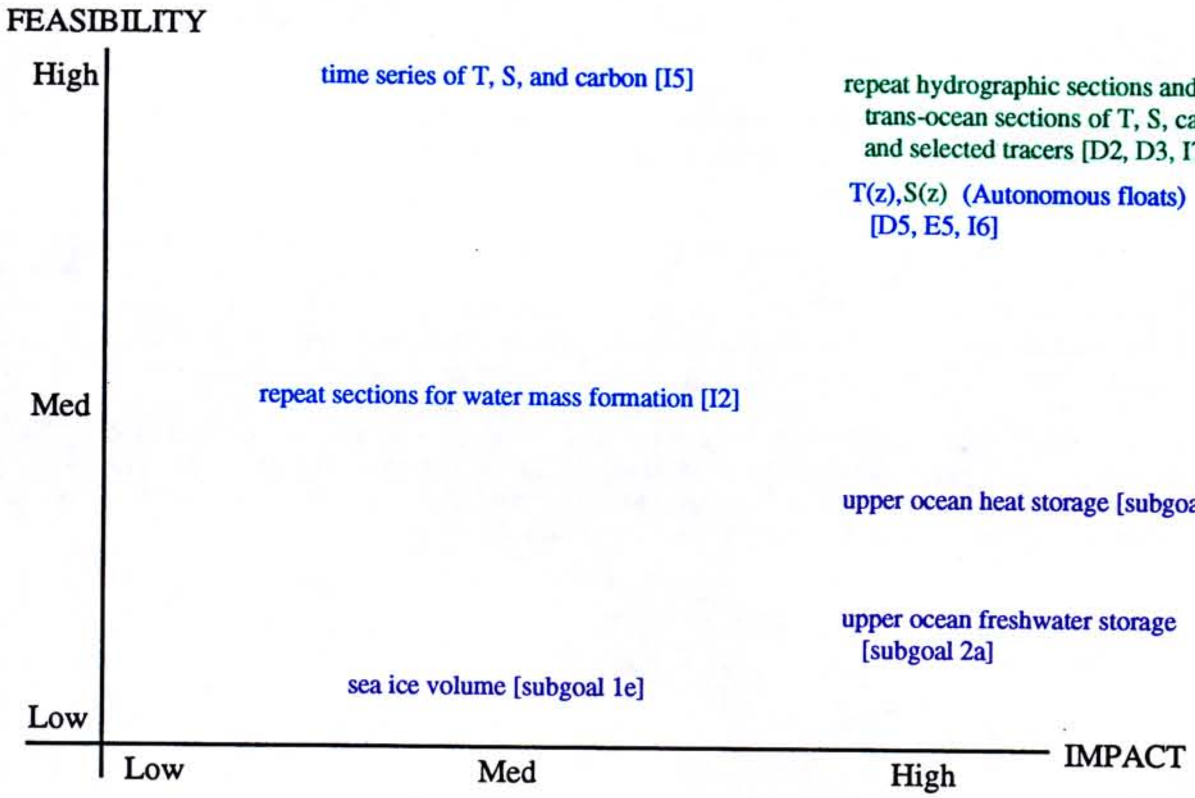
It may however prove necessary, in addition to the minimum set of requirements given above, to obtain large-scale thermal data in the upper ocean from an expanded program of VOS XBT observations and/or the use of profiles from autonomous floats. Other types of data may be required on regional scales.

Alternative observational elements (in approximate order of priority) are:
- subsurface temperature from VOS and floats and
- currents from drifters and ADCPs.

For some regions it is possible to gather enough in situ upper ocean temperature data to monitor upper ocean variability including boundary currents. When merged with satellite SST data it is possible to reconstruct the fine-scale subsurface structure ("feature" analysis). Drifters and ADCP data from VOS and research vessels provide additional information. For this subgoal such data sets and analyses (and perhaps predictions) can be viewed as regional "pilot" observing systems from which a more general, global system might be evolved.

Deficiencies. The outcomes from this system are limited both by available data and by lack of scientific knowledge. The implementation of a basic observing system will rely on technological developments and on ongoing research programs such as CLIVAR. In the meantime, the observing system must foster regional activities even if they may not be entirely within the present definition of ocean climate.

Figure VIII.A.2-9. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 3a: To provide data to determine the changes in oceanic storage and inventories of heat, fresh water, and carbon on large space and long time scales.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

Changes in the heat, fresh water, and carbon content of the full depth ocean on large space and long time scales are sensitive indicators of climate change. They are indicative of changes in water mass formation and represent the only possibility of observing the small changes in surface fluxes that are predicted to occur with increasing greenhouse gasses. This subgoal is complimentary to subgoal 2a addressing the upper ocean and depends on it. Both address the need for a long-term relentless program of data collection which over time will determine the slowly evolving oceanic heat, fresh water, and carbon storage.

<u>The minimum set of requirements</u> are:

- a program of transocean sections, measuring T, S, carbon, $^{14}C$, and selected tracers;
- profiles of T and S using autonomous floats;
- repeat hydrographic sections in critical regions for water mass formation; and
- upper ocean heat and fresh water content (from subgoal 2a).

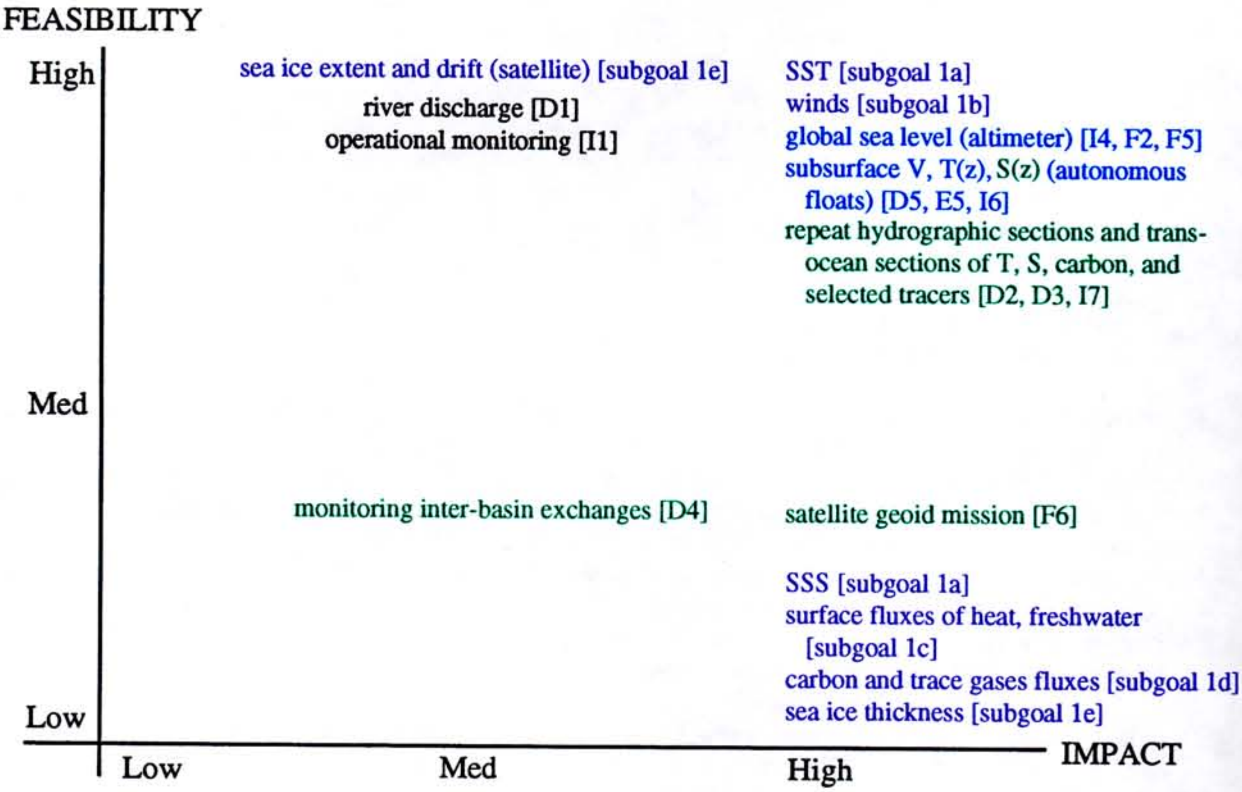
Hydrographic sections are the proven technique for measuring oceanic heat, fresh water, and carbon content and form the basis for measurements of the greatest accuracy. Simultaneous measurements of $^{14}C$ and selected tracers (e.g., chlorofluorocarbons) allow some determination of the age of particular water masses and of their origin. As for subgoal 3b, the interval between repeats of transoceanic sections needs to be determined by experience—such is being obtained from the repeat occupation of sections in the North Atlantic including 24°N in 1957, 1981, and 1993, and by time series of high-density lines of XBT and XCTD observations. Given the uncertainty of the interval between repeats and because of the recent global coverage being provided by WOCE, transocean sections, although essential, have been classified as enhancements to the initial system in this report. Measurement of changes in integrated heat, fresh water, and carbon storage requires distributed observations. Repeat hydrographic stations, required for the determination of heat and freshwater fluxes, contribute to this objective as will high quality data from research programs. Selected tracers should be considered for measurement if they can be used as surrogates to establish carbon inventories. For heat and fresh water content, profiles of T and S from a well distributed array of autonomous floats would provide basic information, especially in remote areas. Repeat sections are also required to monitor water mass formation in certain regions. An example is provided by the yearly spring time occupation of a section across the Labrador Sea which provides information on the extent and characteristics of the yearly formation of Labrador Sea Water by deep convection.

The system would be improved by:
- time series stations of T, S, and carbon and
- measurements of sea ice volume.

Although a time series station only gives information on the local storage of heat, fresh water, or carbon, where they exist, for example Station S off Bermuda, they appear to be representative of a larger area. In addition, they provide information on the variability on seasonal and longer time scales that is vital for the interpretation of the necessarily low temporal resolution of global measurements. Some such stations already exist and should be continued as part of the initial observing system (as indicated in the figure); other selected stations would enhance the observing system. Acoustic thermography offers promise as a tool to observe some low frequency changes in the oceanic thermal structure integrated along the acoustic pathways. However, evaluation of this technique awaits the results of experiments such as ATOC. Global measurements of sea ice volume would further improve our knowledge of freshwater transports and budgets, but seem remote at this time.

Deficiencies. It is clearly a formidable task to measure even the long time, large scale storage of heat, fresh water, and carbon in the face of the known and different time and space scales that exist throughout the water column. Nevertheless, the recommended measurements when interpreted with the aid of information regarding changes in oceanic transports obtained under subgoal 3b are sure to advance our knowledge of this important aspect of climate change. Initially, implementation should be focused on areas where the signal is expected to be large and logistics are feasible, but ultimately global measurements are required.

Figure VIII.A.2-10. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 3b: To provide data to describe changes in the large-scale ocean circulation and its transport of heat, fresh water, and carbon on long time scales.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

This subgoal is concerned with changes in the full depth oceanic circulation on interannual and longer time scales. Given our present knowledge of the deep ocean, it is not concerned with collecting data to initialize deterministic predictions. The objective is rather to describe low frequency changes in the circulation and its related transports of heat, fresh water, and carbon that are known to occur naturally and are predicted in the future as the result of increasing greenhouse gases. Of obvious importance for an optimum design of an ocean observing system to meet this subgoal is the completion of WOCE and JGOFS and the results of future research programs of the WCRP and IGBP. Nevertheless, given present knowledge it is possible to specify a set of systematic observations for this subgoal which need to be maintained for the foreseeable future and which will not in general be supported as part of research programs.

The minimum set of requirements are:

- sea surface elevation from a precision altimeter;
- wind stress and SST (from subgoals 1a and 1b);
- a program of transocean sections, measuring T, S, carbon, $^{14}C$, and selected tracers (e.g. chlorofluorocarbons);
- subsurface velocity and profiles of T and S using autonomous floats;

- sea ice extent and drift (from subgoal 1e); and
- river discharge.

Sea surface elevation obtained from altimetry provides the only presently available global measure of the response of the ocean to changes in surface forcing, especially that related to changes in wind stress which must also be determined. On interannual and longer time scales, there is known to be natural variability in the interior ocean large-scale mass field and the vertical structure of geostrophic currents. Similar changes are predicted to arise from increasing greenhouse gases. Two techniques can be used to quantify the resulting change in the oceanic circulation and its transport of heat, fresh water, and carbon. First, repeat hydrographic sections taken across ocean basins provide a measure of changes in the baroclinic flow and of the transport of heat, fresh water, and carbon across the section. The time interval between repeat occupations of sections needs to be determined by experience and the result of research programs. Analysis of single sections can use the methods introduced by Hall and Bryden (1982) and multiple sections can take advantage of a higher order inverse or model-based techniques. Second, an array of autonomous floats at a deep reference surface provide a direct measurement of the generally weak, but fundamentally important, deep flow as is being shown in WOCE. Such floats, when equipped to measure T and S during regular trips to and from the surface, can provide an evolving three-dimensional description of the T, S, mass, and available potential energy fields suitable for assimilation and analysis by ocean GCMs resulting in a description of circulation variability. To measure the flux of fresh water, observation of river runoff and sea ice extent and drift are required.

The CFCs are valuable tracers to compute and follow the distribution of carbon inventories in the ocean for three main reasons: they are inert compounds; their atmospheric input function is well known (which is not the case for tritium); and there is no pre-anthropogenic background. Until now the use of CFCs to calibrate OGCMs or compute inventories has been restricted by a lack of global, near synoptic data coverage in the past. It is certainly unfortunate that the data collected by numerous investigators over the past 10-15 years has still not been compiled in a single data base. This situation must be improved in the near future. An active international cooperation on measurement and calibration exists today under the WOCE program.

The system would be improved by:

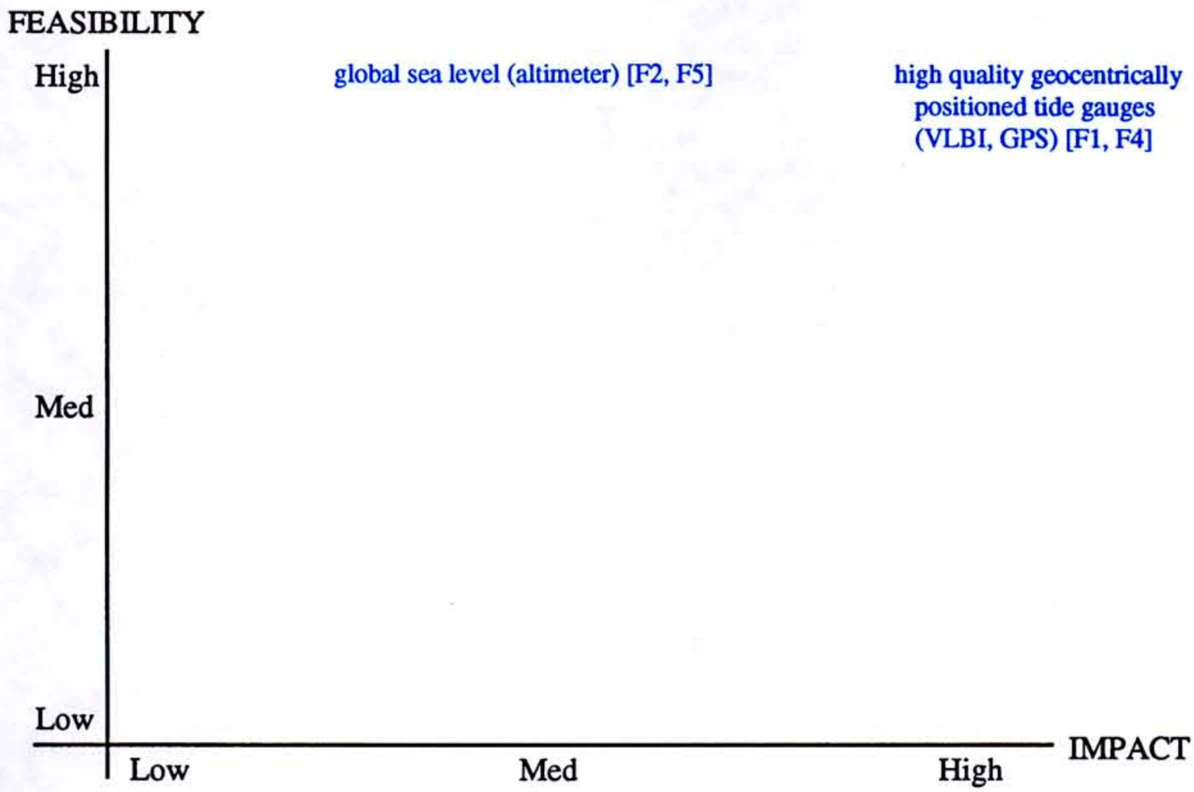
- measurement of inter-basin exchanges;
- boundary current monitoring;
- sea surface fluxes of heat, freshwater, and carbon (from subgoals 1c and 1d);
- SSS and surface $pCO_2$ (from subgoal 1a);
- sea ice thickness; and
- a marine geoid satellite mission.

Measurements of the transports of water, heat, and salt between ocean basins provide strong constraints on the global circulation and its variability. Unfortunately, such measurement now are feasible only where the flow is constricted in a passage of limited width. Two important inter-basin exchanges meeting this criteria are between the Pacific and Arctic Oceans through Bering Strait and between the Indian and Pacific Oceans through the Indonesian passages. Measurements of boundary currents also provide information on changes in the circulation but suffer from difficulties in determining whether changes in the boundary current are compensated by flow elsewhere. However, the existing cable measurement of the Gulf Stream in Florida Strait is an example of a record that should be maintained. Measurement of absolute ocean currents using altimetry is limited by lack of knowledge of the marine geoid. This would be improved by a special dedicated satellite gravity mission. Knowledge of spatial and temporal changes in the surface fluxes of heat, fresh water, and carbon can aid in the interpretation of variability observed in the ocean circulation and the transport of these quantities. However, at present the accuracy to which these fluxes can be determined is such that on long time scales, net fluxes seem to be better determined by interior ocean measurements (see also subgoal 3a). The inability to obtain accurate surface fluxes increases the importance of measuring SST globally and SSS and $pCO_2$ where they can be obtained from VOS.

Deficiencies. The recommended system is limited in its ability to resolve strong current systems (and their transports of heat, fresh water, and carbon) that are of limited spatial extent but are nevertheless important elements of the oceanic circulation. An example is the lack of a viable technique to measure changes in these transports by the ACC through Drake Passage. There is also the inherent difficulty in interpreting long period changes in the circulation and its transports using infrequent measurements in the presence of mesoscale variability. The logistical difficulty of putting in place the recommended measurements globally, especially in the Southern Ocean, is also evident. Nevertheless, the emerging experience of WOCE and development of more realistic ocean models capable of aiding in the interpretation of ocean data indicate that the recommended system is a significant step towards meeting the subgoal.

Improved bathymetry is required in many regions of the global ocean because of the strong effect bottom topographic features such as ridges and passages have on ocean circulation. Without improved bathymetry interpretation of changes in sea surface elevation and the interior mass field in terms of changes in the circulation will remain problematical in some regions.

Figure VIII.A.2-11. Schematic showing impact versus feasibility for elements of the ocean observing system for climate recommended in support of **subgoal 3c: To provide measurements of the long-term change in sea level due to climate change; in particular that arising from greenhouse warming.**




Black = existing operational systems
Blue = to be added to complete the initial observing system
Green = enhancements to initial observing system as feasible
Purple = climate variables provided by another (indicated) subgoal

**Notes**

This subgoal is directed at putting in place the capability to observe the long-term change in sea level expected as a result of increasing greenhouse gases. The likely increase due to oceanic thermal expansion alone has been estimated as 2-4 cm/decade (IPCC, 1992). Additional change could arise from ablation of glaciers and ice sheets. The "observed" change in sea level over the past 50 years has been estimated by Barnett (1983b, 1984) and others from the analysis of tide gauges to be of order 1-2 cm/decade. However, these estimates are uncertain both because of the small number and distribution of tide gauges with sufficient record length and because of the difficulty of accurately accounting for isostatic changes at the location of the tide gauges.

The minimum requirement is for:

- A number of high quality tide gauges (of order 50) geocentrically located in an earth reference system and
- A precision satellite altimeter.

The actual number of gauges required is unknown but must be sufficient to average across the spatial patterns of sea level change due to global warming. A crude estimate can be made as an average of not more than 12 gauges for each of five ocean basins for a total of 60. The design of the network should take into consideration model predictions of the spatial change of global sea level and vertical land motion. The location of gauges should also be such as to minimize the effects of coastal currents and winds which may also change with global warming. Positioning of the tide gauges in an earth reference system requires the combined use of VLBI and GPS (Global Positioning System). When possible it will be beneficial to use existing tide gauge stations with long consistent records.

A TOPEX/POSEIDON quality altimeter would allow resolution of the spatial pattern of sea level change. It could also result in a reduced requirement for geocentrically positioned tide gauges. However, reduction would be unwise until both an altimeter is guaranteed in the long-term and any questions of maintaining the integrity of altimeter orbits in the earth reference system are resolved.

Deficiencies. The suitability of existing and potential tide gauge sites should be studied in the context of designing a network to measure estimated patterns of global sea level change. In addition, expert agreement needs to be obtained on the best methodology for establishing a geodetic geocentric reference frame and siting the tide gauges in it.

## VIII.B. Immediate Subgoals and Needed Observations

### VIII.B.1 Recommended subgoal priority

The OOSDP assigned priority to each subgoal using as a guide the general criteria of impact and feasibility. That is to say that higher priority is assigned to subgoals for which the observations of highest impact are currently attainable, so that the goal likely will be met. To some extent priority has been given to subgoals where immediate attention is needed to continue research systems of proven utility (for example, elements of the TOGA network) or there is a serious environmental concern (for example, global sea level change). It is to be noted that the elements required to meet one subgoal often contribute to other subgoals (see following Section VIII.B.2).

The Panel's ranking of the subgoals is given in Table VIII.B.1-1. Four ranks of priority were used. Within a numbered rank, the absolute position of one subgoal relative to another is unsure. In addition, it should be noted that the Panel gives priority to meeting all of the subgoals and that their selection and definition in Section III is a reflection of that priority.

| Subgoal | | Ranking |
|---|---|---|
| 1a | SST | 1 |
| 1b | Wind and wind stress | 1 |
| 1c | Heat and freshwater air-sea fluxes | 2 |
| 1d | Surface carbon fluxes | 2 |
| 1e | Ice | 2 |
| 2a | Upper ocean monitoring | 2 |
| 2b | Pacific ENSO prediction | 1 |
| 2c | Global seasonal-interannual prediction | 4 |
| 3a | Global inventories | 3 |
| 3b | Circulation and transport | 4 |
| 3c | Sea level change | 1 |

Table VIII.B.1-1. Subgoal Priority

### VIII.B.2 Priority of observational elements

The selected order of priority of the subgoals given in Table VIII.B.1-1 provides guidance on the order of priority that should be given to the implementation of the elements of the observing system. This is shown in Table VIII.B.2-1, which lists the subgoals in order of their stated priority (within each rank of priority the order is in numerical and alphabetic order). The table also lists all the observing system elements of category 2; that is, the elements that are to be added now to constitute the initial observing system and which are shown in blue on the feasibility-impact diagrams. Also listed are the elements of category 1; that is, elements of existing operational systems, which are shown in black on the feasibility-impact diagrams. Table VIII.B.2-1 does not include elements of category 3; that is, enhancements of the initial system to be added when feasible.

In listing the observational elements, Table VIII.B.2-1 shows for each subgoal only those category 2 elements that have not been already introduced in support of subgoals of higher level in the table.

Table VIII.B.2-1. Summary of existing operational elements and elements to be added now to complete the initial observing system recommended for each subgoal. The subgoals are ordered by priority assigned by the OOSDP. Elements to be added now in support of a subgoal may contribute to other subgoals, as indicated, illustrating the complex relations between the various subgoals and observational elements.

| Subgoal | Priority or Rank | Elements of existing operational systems (category 1) | Elements to be added to constitute the initial observing system (category 2) | Lower ranked subgoals supported by element | Higher ranked subgoals and elements thereof that support this subgoal |
|---|---|---|---|---|---|
| 1a. SST, SSS | 1 | global satellite SST (AVHRR)<br>VOS reporting SST<br>moored and buoy SST | 1) use of ATSR<br>2) SST on quality VOS<br>3) SST on more drifters<br>4) SST & SSS on TAO | 1b, 1c, 1d, 2a, 2b, 2c, 3b<br>1b, 1c, 1d, 2a, 2b, 2c, 3b<br>1b, 1c, 1d, 2a, 2b, 2c, 3b<br>1b, 2b | |
| 1b. Wind and wind stress | 1 | VOS met observations<br>NWP model analyses<br>SLP from buoys<br>altimeter wind speed | 5) scatterometer<br>6) TAO array winds<br>7) SLP in S. Hemisphere<br>8) Improvement of VOS winds | 1c, 1d, 2a, 2b, 2c, 3b<br>2b<br>1c, 1d, 2a, 2b, 2c, 3b<br>1c, 1d, 2a, 2b, 2c, 3b | 1a |
| 2b. ENSO prediction | 1 | operational SST and wind analysis<br>in situ sea level | 9) T(z) from VOS<br>10) T(z) from TAO<br>11) V(z) from TAO<br>12) precision altimeter | 2a<br>2a<br><br>2a, 2c, 3b, 3c | 1a, 1b (especially elements 4 and 6, TAO array SST and winds) |
| 3c. Global sea level change | 1 | nil | 13) high quality geocentrically located tide gauges | | 12 (precision altimeter) |
| 1c. Surface heat and water fluxes | 2 | operational wind and SST analyses<br>NWP fluxes<br>existing VOS met observations<br>satellite radiation & precipitation<br>met buoy data | 14) improved VOS met observations<br>15) in situ radiation<br>16) regional flux verification (buoys) | 1d, 2a, 3b<br>2a, 3b<br>2a, 3b | 1a, 1b |
| 1d. Surface $CO_2$ flux | 2 | nil | 17) $pCO_2$ from manned VOS<br>18) fluorescence from manned VOS | 3b<br>3b | 1a, 1b, 1c |
| 1e. Sea ice | 2 | sea ice extent & concentration (satellite microwave) | 19) ice drifters<br>20) in situ ice thickness | 3b<br>3a, 3b | |
| 2a. Upper ocean monitoring | 2 | regional upper ocean monitoring | 21) T(z) (global VOS broadcast XBTs)<br>22) T(z) (S. Hemisphere supply vessels)<br>23) T(z) (autonomous floats) | 3a<br>3a<br>3a, 3b | 1a, 1b, 1c, 12 (precision altimeter) |
| 3a. Global inventories | 3 | nil | 24) time series T, S, and carbon<br>25) repeat sections for water mass formation | | 1e, 2a |
| 2c. Global seasonal to interannual prediction | 4 | nil | nil | | 1a, 1b, 2a, 2b, 12 (precision altimeter), 21 (VOS T(z)), 23 (T(z) from autonomous floats) |
| 3b. Global circulation and transport | 4 | national long-term operational sections, river discharge monitoring | nil | | 1a, 1b, 1c, 1d, 1e, 12 (precision altimeter), 23 (T(z) from autonomous floats) |

To show the extent to which category 2 elements introduced to meet higher priority subgoals can contribute to those given lower priority, the table shows the subgoals of lower order in the table to which each element contributes. Similarly, the table shows higher ranking subgoals and/or the category 2 observational elements (which are numbered) by which each subgoal is supported. It is to be noted that the order in which an observational element is introduced within subgoals with the same rank is somewhat arbitrary (numerical order). Thus, the precision altimeter, which is of great importance to several subgoals, is introduced in support of subgoal 2b (ENSO prediction) in Table VIII.B.2-1 rather than subgoal 3c (global sea level change) to which it is of more inherent importance. Indeed, the interpretation of the relative impact of observations in meeting any particular subgoal and the dependence of observations on each other can only be determined by reference to Section V and/or the feasibility-impact diagrams.

The contribution made by the category 2 observational elements required for the subgoals of higher rank to a number of subgoals of lower rank in Table VIII.B.2-1 is striking. Indeed, within this analysis the required category 2 observational elements for subgoals 2c and 3b are completely provided by higher ranked subgoals.

However, it must be reiterated that the table does not include elements of category 3. All of these are essential if the observing system for climate is to satisfy the full requirements of the subgoals. While some elements were classified as category 3 because they require further research and development as specified in Section V, other elements have not been included as category 2 for reasons of their immediate priority and concern regarding the total cost of the system. For example, the repeat hydrography and the transocean sections of T, S, carbon, and selected tracers have been listed as category 3 (elements to be added later as feasible) even though they are *essential* to attaining subgoals 3a and 3b. They lack some urgency because of the global coverage now being provided by WOCE and because their inclusion would require long term commitments (at least commitments with repeat terms of five to 10 years) that nations are unlikely to make to an operational observing system at this time.

## VIII.C. A Coherent Conceptual Design for the Observing System

The observations recommended here for the system must be taken, quality controlled, transmitted and archived, as described in Section VI. To ensure that the observing system is properly operating and evolving to take advantage of new developments without compromising the needed long data records, the OOSDP is convinced of the need for ongoing self evaluation as part of the system. The functions which must be carried out include, among others, detailed monitoring of performance, assessment of technical developments, and examination of strategic tradeoffs. These are the functions of the evaluation unit described in Section VII.D. Its support is essential for the successful implementation of the ocean observing system for climate.

This final section discusses additional activities needed to help ensure a coherent, effective ocean observing system for climate, the common module of GOOS and GCOS. The preceding discussion in this section is focused on delivering the information required to fulfill particular goals and subgoals. Here we concentrate on the delivery of the information and products that together will fulfill the general goal (i.e., provide the "whole" ocean observing system for climate).

The cohesive fabric for this final step is provided by the suite of processing activities which ingest observations from disparate sources and output high quality, useful products for the user community of this observing system. On some occasions this may require several steps, the scientific analysis being an intermediate step toward a more readily understood and comprehensible representation of the original information.

It is important that the processing pathways from measurements to user products are able to take full advantage of the available information. The effectiveness and efficiency of these connections is of fundamental importance if the "owners" of the observing system are going to be able to fully exploit its potential. It is equally critical that these processing pathways are constructed and presented in such a way that the users of the products are able to appreciate and understand the key role of the basic observing system. In other words, the observing system should not simply be a "black box" providing information; rather, it should be seen and appreciated as the fundamental strength of the system, including its products.

For some activities such processing chains (data → products) will be a novel development, so a certain level of experimentation should be expected and accepted. In this respect, it is important to have adequate and effective connections to, and guidance from, the research community.

While there will be many pathways from observations to products, we will try to represent the essence of the process through three streams of activity.

1) Climate assessment. One of the principal motivations for a global climate observing system is the possible change in the earth's climate due to anthropogenic effects (e.g., the enhanced Greenhouse effect). The OOSDP response to this issue is to recommend the establishment of an ongoing climate assessment activity (center or centers) with the principal aim of providing regular, state-of-the-art assessments of the state of the (ocean) climate.
2) Model development and validation. A theme through the discussion of observing elements in Section V is the need to include models in network design, quality control, interpretation of data, and in the projection of information in space and time (mapping and forecasts). One responsibility of the observing system designers is to ensure that models reliably and faithfully represent the relevant oceanic processes.
3) Numerical ocean prediction. TOGA and related activities have brought oceanography to the point where useful climate forecasts (seasons to several years) are now thought to be attainable. The OOSDP recommends that forecasting capability be achieved through facilities/activities dedicated to the processing of relevant data and producing forecasts and related applied products. Initially, the focus will be on seasonal to interannual prediction but in time may evolve into a more general ocean prediction capability. (The processing by numerical weather prediction centers, e.g., to obtain wind stress, will not be discussed here because this is foremost an issue for the meteorological community.)

### VIII.C.1 Climate assessment activity

This activity will concentrate on ocean changes on large spatial scales and long time scales (order of a decade or longer). The aim is to bring to bear the power and immense information content of the ocean climate data base to give a timely, regular (perhaps biannual) assessment of the ocean state and its impact on earth's climate. This is not simply a case of incorporating new information but of using improved knowledge and processing power to interpret and quality control past data. It is an undertaking of processing and filtering and thoughtful compression of complex information into a form which permits those responsible for safeguarding/sustaining our environment to make advised decisions. The process used for IPCC assessments is a useful model for this activity. The goal of the processing units would not be to produce an "IPCC update" but to ensure that those charged with such a responsibility were fully acquainted with and had access to the best possible interpretations of the current data holdings. Other users will include government agencies of all nations as well as the commercial sector and climate researchers.

The center or centers for this assessment activity should be located alongside research activities. They require full-time, dedicated personnel. The activity requires ready access to all information from the observing system as well as to the historical data sets. This activity as well as those to follow will provide an opportunity for many nations to contribute to and benefit from the ocean observing system for climate.

## VIII.C.2 Model improvement and validation

The aim of this activity is to ensure that the ocean data interpretation tools faithfully represent the relevant dynamic constraints and processes of the actual ocean and its role in climate. The tools are normally ocean models of varying degrees of sophistication. The models are not a substitute for observations, but instead add value through exporting information to regions in which direct sampling is not undertaken. It is important that the design of the observing system accommodate mechanisms for ensuring, as far as is practical, that the models are effective and efficient and appropriate to the tasks (e.g., in models for sea level rise); that the observations are adequate to detect the introduction of systematic errors (bias or variability) of the model; and that the data are available to validate the simulated spectrum of variability.

The system should provide data and perhaps compressed representations (summaries) of the data, which can be used to assess how faithfully the model is representing the actual ocean. Model validation is essential if the observing system is to evolve and progress. Only by testing models against actual data can we ensure that the tools used to process information will continue to improve. This will not happen as a matter of course but will require positive actions to bring the data into the modeling community in a form that is easy use and understand.

## VIII.C.3 Numerical prediction

Ideally, we would like the observing system to support global coupled atmosphere-ocean prediction efforts. In reality, this is now only feasible for seasonal to interannual predictions involving the tropical Pacific Ocean and the atmosphere. The OOSDP recognizes that the best way to utilize the existing and planned observing network is to have dedicated activities which routinely analyze the available data and use it as a basis for making forecasts and other products. Regular use of data and evaluation of products provides the best strategy for optimizing and improving observing system design. There are already several quasi-operational activities pursuing a useful predictive capability for ENSO. It is envisaged that further progress will depend on dedicated centers with the resources and user community to foster and develop operational systems for the collection and analysis of data and their use in the initialization of climate prediction models. The fundamental role for these centers in the ocean observing system is to develop the tools and processing facilities to exploit the ocean data base to the extent possible in producing useful climate outlooks/forecasts for the regions affected by the seasonal/interannual variability in the ocean. As/if prediction of longer-term variability becomes feasible, the processing activities will be expanded to include outlooks and forecasts for these time scales.

Through NOAA, the U.S. is proposing an international SCPP. This is envisioned as a network to include research centers, within which an International Research Institute would be established with the responsibility of producing, assessing, and distributing experimental climate forecast guidance products to interested nations on a regular basis. Also, as part of this program network, it is proposed to establish Regional Applications Centers in participating countries to develop regional forecasts and distribute products of social and economic benefit.

Note that each of the three foregoing activities will depend to some extent on the total information in the observing system data base, not just on elements dedicated to the particular goal or phenomenon. It is this cross-utilization of information that provided the strength in the total conceptual design (e.g., Table VIII.B.2-1). It will be the responsibility of the bodies charged with scientific oversight of GOOS and its modules to continually review and evaluate the system, and to suggest changes which improve its scientific products and processing and which maximize the economic and social benefits.

## References


Aagaard, K., J. H. Swift, and E. C. Carmack. 1985. Thermohaline Circulation in the Arctic Mediterranean Seas. *J. Geophys. Res.*, 90(C3): 4833-4846.

Adams, R. M., B. A. McCarl, K. Bryant, A. Solow, and D. Legler. 1994. The value of improved ENSO forecasts: an example from U.S. agriculture. *Nature*, in review.

Allison, I. and R. E. Moritz. 1995. Sea Ice in the Global Climate System: Requirements for an Ocean Observing System, Ocean Observing System Development Panel, Texas A&M University, College Station, TX. In press.

Allison, I., R. E. Brandt, and S. G. Warren. 1993. East Antarctic sea ice: albedo, thickness distribution, and snow cover. *J. Geophys. Res.*, 94: 14, 485-14,498.

Anderson, D. L. T. and A. M. Moore. 1989. Initialization of equatorial waves in ocean models. *J. Phys. Oceanogr.*, 19: 116-121.

Anderson, D. L. T. and J. Willebrand. 1992. Recent advances in modeling the ocean circulation and its effect on climate. *Reports on Progress in Physics*, 55: 1-36.

Arkin, P. A. and P. E. Ardanuy. 1989. Estimating Climatic-Scale Precipitation from Space: A Review. *J. Climate*, 2: 1229-1238.

Armi, L. and H. Stommel. 1983. Four views of a portion of the North Atlantic subtropical gyre. *J. Phys. Oceanogr.*, 13(5): 828-857.

Bacastow, R. B. and E. Maier-Reimer. 1990. Ocean circulation model of the carbon cycle. *Climate Dyn.*, 4: 95-125.

Baggeroer, A. and W. H. Munk. 1992. The Heard Island Feasibility Test. *Physics Today*, 45: 22-30.

Bailey, R., A. Gronell, H. Phillips, E. Tanner, and G. Meyers. 1994. Quality control cookbook for XBT data: Version 1.1. CSIRO Marine Laboratories Report No. 221, CSIRO Marine Laboratories, Castray Esplanade, Hobart, Australia. 84 pp. ·

Barber, R. T. and F. P. Chavez. 1983. Biological consequences of El Niño. *Science*, 222: 1203-1210.

Barnett, T. P. 1983a. Interaction of the monsoon and the Pacific trade wind system at interannual time scales. Part I: the equatorial zone. *Mon. Wea. Rev.*, 111: 756-777.

Barnett, T. P. 1983b. Recent changes in the sea level and their possible causes. *Climate Change*, 5: 15-38.

Barnett, T. P. 1984. Estimation of "global" sea level change: a problem of uniqueness. *J. Geophys. Res.*, 89: 7980-7988.

Barnett, T. P., N. Graham, M. A. Cane, S. E. Zebiak, S. Dolan, J. O'Brien, and D. Legler. 1988. On the prediction of the El Niño of 1986-87. *Science*, 241: 192-196.

Barnier, B. and J. Y. Simonot. 1990. Net surface heat flux over the north and south Atlantic in 1985-1986 from day 1 predictions of the European Center for Medium-Range Weather Forecast. *J. Geophys. Res.*, 95(C8): 13,301-13,311.

Bates, J. J. and H. F. Diaz. 1991. Evaluation of multichannel sea surface temperature product quality for climate monitoring: 1982-1988. *J. Geophys. Res.*, 96(C11): 20,613-20,622.

Bates, T. 1992. Sulfur, Aerosols and Climate. Scientific Rationale for a Global Ocean Observing System to Monitor Oceanic Dimethylsulfide and the Chemical and Physical Properties of Atmospheric Aerosol Particles. Annex IV of the OOSDP-V meeting report. CCCO-JSC/OOSDP-V/3. 46 pp.

Battisti, D. 1988. Dynamics and thermodynamics of a warming event in a coupled tropical atmosphere-ocean model. *J. Atmos. Sci.*, 45: 2889-2918.

Bauer, S., G. L. Hitchcock, and D. B. Olson. 1991. Influence of monsoonally-forced Ekman dynamics upon surface layer depth and plankton biomass distribution in the Arabian Sea. *Deep-Sea Res.*, 38(5): 531-553.

Baumgartner, A. and E. Reichel. 1975. The World Water Balance. New York: Elsevier. 179 pp.

Bennett, A. F. 1992. Inverse methods in physical oceanography. Cambridge monographs on Mechanics and Applied Mathematics, Cambridge University Press, New York. 346 pp.

Bishop, J. K. and W. B. Rossow. 1991. Spatial and temporal variability of global surface solar irradiance. *J. Geophys. Res.*, 96(C9): 16,839-16,858.
Böning, C. W. and P. Herrmann. 1994. On the annual cycle of poleward heat transport in the ocean: Results from high resolution modeling of the North and equatorial Atlantic. *J. Phys. Oceanogr.*, 24: 91-107.
Bottomley, M., C. K. Folland, J. Hsuing, R. E. Newell, and D. E. Parker. 1990. Global Ocean Surface Temperature Analysis "GOSTA". Joint project of the Meterological Office and Massachusetts Institute of Technology, supported by the U.S. Department of Energy, U.S. National Science Foundation, and U.S. Office of Naval Research. Publication funded by UK Departments of the Environment and Energy for the Intergovernmental Panel on Climate Change. Printed by HMSO, London, 20 pp + iv, 313 plates.
Braconnot, P. and C. Frankignoul. 1994. On the ability of the LODYC GCM to simulate the thermocline depth in the equatorial Atlantic. *Clim. Dyn.*, 9: 221-234.
Bradley, E. F., J. S. Godfrey, P. A. Coppin, and J. A. Butt. 1993. Observations of net heat flux into the surface mixed layer of the western equatorial Pacific Ocean. *J. Geophys. Res.*, 98: 22,521-22,532.
Bretherton, F. P., R. E. Davis, and C. B. Fandry. 1976. A technique for objective analysis and design of oceanographic experiments applied to MODE-73. *Deep-Sea Res.*, 23: 559-582.
Bretherton, F. P., M. J. McPhaden, and E. B. Kraus. 1984. Design studies for climatological measurements of heat storage. *J. Phys. Oceanogr.*, 14: 318-337.
Briscoe, M. G. and D. E. Frye. 1987. Motivation and methods for ocean data telemetry. *J. Mar. Technol. Soc.*, 21: 42-57.
Broecker, W. S. 1987. Unpleasant surprises in the greenhouse? *Nature*, 328: 123-126.
Broecker, W. S. and T.-H. Peng. 1982. Tracers in the Sea. Publication of Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY. 690 pp.
Broecker, W. S., D. M. Peteet, and D. Rind. 1985. Does the ocean-atmosphere system have more than one stable mode of operation?, *Nature*, 315: 21-26.
Brooks, D. A. and M. G. Briscoe. 1991. Test of Long-Range Ocean Data Telemetry Using Frequency-agile HF Packet-switching Protocols. *J. Atmos. Ocean. Tech.*, 8(6): 856-868.
Bryden, H. L. 1993. Ocean Heat Transport Across 24°N Latitude. *Interactions between Global Climate Subsystems, the Legacy of Hann.* Geophysical Monograph 75, IUGG Volume 15, 65-84.
Bryden, H. L. and E. C. Brady. 1989. Eddy momentum and heat fluxes and their effect on the circulation of the equatorial Pacific Ocean. *J. Mar. Res.*, 47: 55-79.
Bryden, H. L., E. C. Brady, and R. D. Pillsbury. 1988. Flow through the Strait of Gibraltar. The Gibraltar Symposium, Madrid, October 24-29, 1988.
Bryden, H. L., D. H. Roemmich, and J. A. Church. 1991. Ocean Heat Transport Across 24°N in the Pacific. *Deep-Sea Res.*, 38(3): 297-324.
Budyko, M. I. 1963. Atlas of the heat balance of the world. [In Russian]. Glavnaia Geofizicheskaia Observatoriia, Moscow, 69 pp.
Budyko, M. I. 1974. Climate and Life. Academic Press, New York, 508 pp.
Bunker, A. F. 1976. Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. *Mon. Wea. Rev.*, 104: 1122-1140.
Cadet, D. L. and B. C. Diehl. 1984. Interannual variability of surface fields over the Indian Ocean during recent decades. *Mon. Wea. Rev.*, 112: 1921-1935.
Cane, M. A. 1983. Oceanographic events during El Niño. *Science*, 222: 1189-1195.
Cane, M. A., S. C. Dolan, and S. E. Zebiak. 1986. Experimental forecasts of the 1982-1983 El Niño. *Nature*, 321: 827-832.
Cardone, V.J., J. G. Greenwood, and M. A. Cane. 1990. On trends in historical marine wind data. *J. Climate*, 3: 113-127.
Carissimo, B. C., A. H. Oort, and T. H. Vonder Haar. 1985. Estimating the meridional energy transports in the atmosphere and ocean. *J. Phys. Oceanogr.*, 15: 82-91.
Carleton, A. M. 1981. Monthly variability of satellite derived cyclonic activity for the Southern Hemisphere winter. *J. Climatol.*, 1: 21-38.

Carter, D. J. T. 1992. Accuracy of monthly means. Unpublished manuscript, available from author at IOSDL, Wormley, Surrey, UK.

Catopovic, J., D. Brady, and S. Etchemendy. 1993. Development of underwater acoustic modems and networks. *Oceanography*, 6(3): 112-119.

Cavalieri, D. J. and C. L. Parkinson. 1987. On the relationship between atmospheric circulation and the fluctuations in the sea ice extents on the Bering and Okhotsk seas. *J. Geophys. Res.*, 92(C7): 7141-7162.

Cavalieri, D. J., J. R. Crawford, M. R. Drinkwater, D. T. Eppler, L. D. Farmer, R. R. Jentz, and C. C. Wakerman. 1991. Aircraft active and passive microwave validation of sea ice concentration from the DMSP SSM/I. *J. Geophys. Res.*, 96: 21,989-22,008.

Cayan, D. R. 1992a. Latent and sensible heat flux anomalies over the northern oceans: driving the sea surface temperatures. *J. Phys. Oceanogr.*, 22(8): 859-881.

Cayan, D. R. 1992b. Latent and sensible heat flux anomalies over the northern oceans: the connection to monthly atmospheric circulation. *J. Climate*, 5(4): 354-369.

Cayan, D. R. 1992c. Variability of latent and sensible heat fluxes estimated using bulk formulae. *Atmos. Ocean*, 30(1): 1-42.

CCCO. 1992. Report of the Joint Meeting of the JSC/CCCO Working Group on Air Sea Fluxes and the WOCE Surface Layer Scientific Panel, 21-25 October 1991. Reading, UK. Available from IOC, Paris.

Chahine, M. T. 1992. The hydrological cycle and its influence on climate. *Nature*, 359: 373-380.

Charlson, R. J., S. E. Schwartz, J. M. Hales, R. D. Cess, J. A. Coakley, J. E. Hansen, and D. J. Hofmann. 1992. Climate forcing by anthropogenic aerosols. *Science*, 255: 423-430.

Chelton, D. B., M. G. Schlax, D. L. Witter, and J. G. Richman. 1990. Geosat altimeter observations of the surface circulation of the Southern Ocean. *J. Geophys. Res.*, 95: 17,877-17,903.

Cheney, R. E. and J. G. Marsh. 1981. Seasat altimeter observations of dynamic topography in the Gulf Stream Region. *J. Geophys. Res.*, 86: 473-483.

Chertok, B. 1989. Global monitoring of net solar irradiance at the ocean surface using Nimbus 7 satellite data. Ph.D. dissertation, University of California at San Diego. 118 pp.

Chester, D. B. 1993. A tomographic view of the Gulf Stream southern recirculation gyre at 38°N, 55°W. Ph.D. thesis. Massachusetts Institute of Technology/Woods Hole Oceanographic Institution, WHOI-93-28.

Chester, D. B. and P. Malanotte-Rizzoli. 1994. A tomographic view of the Gulf Stream southern recirculation gyre at 38°N, 55°W: structure and variability. *J. Geophys. Res.*, submitted.

Chester, D. B., P. Malanotte-Rizzoli, J. Lynch, and C. Wunsch. 1994. The eddy radiation field of the Gulf Stream as measured by ocean acoustic tomography. *Geophys. Res. Letters*, in press.

Clancy, R. M. 1992. Operational modelling: Ocean modelling at the Fleet Numerical Oceanography Centre. *Oceanography*, 5: 31-35.

Clancy, R. M. and K. D. Pollack. 1983. A real-time synoptic ocean thermal analysis/forecast system. *Progr. Oceanogr.*, 12: 383-424.

Clancy, R. M. and W. D. Sadler. 1992. The Fleet Numerical Oceanography suite of oceanographic models and products. *Weather and Forecasting*, 7: 307-327.

Clarke, R. A. and J. C. Gascard. 1983. The formation of Labrator Sea Water. Part I: Large-scale processes. *J. Phys. Oceanogr.*, 13: 1764-1778.

Clarke, R. A. and P. Rapp. 1984. *Reun. Cons. Perm. Inst. Explor. Mer.*, 185: 120-130.

Clarke, R. A., J. H. Swift, J. L. Reid, and K. P. Koltermann. 1990. The formation of Greenland Sea Deep Water: double diffusion or deep convection? *Deep-Sea Res.*, 37(9): 1385-1424.

Coachman, L. K. and K. Aagaard. 1988. Transports through Bering Strait: annual and interannual variability. *J. Geophys. Res.*, 93: 15,535-15,539.

Colossi, J. and T. P. Barnett. 1990. The characteristic spatial and temporal scales for SLP, SST, and air temperature in the southern hemisphere. *J. Appl. Met.*, 29: 694-703.

Comiso, J. C. 1990. Multiyear ice classification and summer ice cover using Arctic passive microwave data. *J. Geophys. Res.*, 95: 13,411-13,422.

Cornillon, P. 1989. Sea surface temperature products for the oceanographic research community: *A report of the sea surface temperature archiving science working group*. NASA and NOAA, 36 pages.
Cowen, R. C. 1985. Payoffs in long-term weather forecasts. *Technology Review*, January: 6.
Cubash, U., B. D. Santer, A. Hellbach, G. Hegerl, H. Hock, E. Maier-Reimer, U. Mikolajewicz, A. Stössel, and R. Voss. 1992. Monte Carlo Climate Change Forecasts with a global coupled ocean-atmosphere model. Max-Plank-Institut für Meteorologie Report, No. 97. 43 pp.
Curtin, T. B., J. G. Bellingham, J. Catapovic, and D. Webb. 1993. Autonomous oceanographic sampling networks. *Oceanography*, 6(3): 86-94.
Dacey, J. W. H. and S. G. Wakeham. 1986. Oceanic dimethylsulfide: production during zooplankton grazing on phytoplankton. *Science*, 233: 1314-1316.
Davis, R. E. 1991. Observing the general circulation using floats. *Deep-Sea Res.*, 38(Suppl. 1): S531-S571.
Delcroix, T. and C. Hénin. 1989. Mechanisms of subsurface thermal structure and sea surface thermohaline variabilities in the southwestern tropical Pacific during 1975-1985. *J. Mar. Res.*, 47: 777-812.
Delcroix, T. and C. Hénin. 1991. Seasonal and interannual variations of sea surface salinity in the tropical Pacific ocean. *J. Geophys. Res.*, 96(C12): 22,135-22,150.
Delworth, T., S. Manabe, and R. J. Stouffer. 1993. Interdecadal variability of the thermohaline circulation in a coupled ocean-atmosphere model. *J. Climate*, 6: 1993-2011.
Deser, C. and M. L. Blackmon. 1993. Surface Climate Variations over the North Atlantic Ocean during Winter: 1900-1989. *J. Climate*, 6(9): 1743-1753.
Dessureault, J.-G. and R. A. Clarke. 1994. A system to collect temperature and salinity profiles from vessels underway. Proceeding of Oceans '94 Conference, IEEE: I397-I401.
Dickey, T., T. C. Granata, and I. Taupier-Letage. 1992. Automated in situ observations of upper ocean biogeochemistry, bio-optics, and physics and their potential use for global studies. *Proceedings of the Ocean Climate Data Workshop*, February 18-21, 1992, Goddard Space Flight Center, Greenbelt, Maryland, U.S. NOAA and NASA publ., pp. 317-353.
Dickson, R. R. 1983. Global summaries and inter comparisons: flow statisitcs from long-term current meter moorings. In: Eddies in Marine Science, A. R. Robinson, ed. Springer-Verlag, Berlin. 609 pp.
Dickson, R. R. 1989. Flow statistics from long-term current-meter moorings: The global data-set in January 1989. *World Ocean Circulation Experiment Report*, WCRP 30, WMO/TD - No. 337.
Dickson, R. R., J. Meincke, S. A. Malberg, and A. J. Lee. 1988. The Great Salinity Anomaly in the northern North Atlantic 1968-1982. *Prog. Ocean.*, 20: 103-151.
Dickson, R. R., E. M. Gmitrowicz, and A. J. Watson. 1990. Deep-water renewal in the northern North Atlantic. *Nature*, 344: 848-850.
Dobson, F. W. and S. D. Smith. 1988. Bulk models of solar radiation at sea. *Royal Met. Soc.*, 114: 165-192.
Donguy, J. R. 1994. Surface and subsurface salinity in the tropical Pacific Ocean. Relations with climate. *Prog. Ocean.*, 34: 45-78.
Dorman, C. E. and R. H. Bourke. 1979. Precipitation over the Pacific Ocean, 30°S to 60°N. *Mon. Wea. Rev.*, 107: 896-910.
Dorman, C. E. and R. H. Bourke. 1981. Precipitation over the Atlantic Ocean, 30°S to 70°N. *Mon. Wea. Rev.*, 109: 554-563.
Duing, W. and F. Schott. 1978. Measurements in the source current of the Somali Current during monsoon reversal. *J. Phys. Oceanogr.*, 8: 278-289.
Edson, J. B., C. W. Fairall, S. E. Larsen, and P. G. Mestayer. 1991. A study of the inertial dissipation technique for computing air-sea fluxes. *J. Geophys. Res.*, 96: 10,689-10,711.
Enfield, D. B. 1989. El Niño, past and present. *Reviews of Geophysics*, 27: 159-187.
Enomoto, H. and A. Ohmura. 1991. Fluctuations of sea ice extent in the Antarctic. *Proc. Natl. Inst. Polar Res. Symp. Polar Meteorol. Glaciol.*, 4: 58-73.

Ezraty, R. 1989. Use of in situ data for verification of satellite wind velocity or stress estimates both for initial calibration/validation and also longer term monitoring. Unpublished manuscript.

Falkowski, P. G., Y. Kim, Z. Kolber, C. Wilson, C. Wirick, and R. Cess. 1992. Natural versus anthropogenic factors affecting low-level cloud albedo over the north Atlantic. *Science*, 256: 1311-1313.

Festa, J. F. and R. L. Molinari. 1992. An evaluation of the WOCE volunteer observing ship XBT network in the Atlantic. *J. Atmos. Oceanic. Technol.*, 9: 305-317.

Fieux, M., C. Andrié, A. G. Ilahude, A. Kartavtseff, R. Molcard, and J. Swallow. 1992. Some results of the JADE experiment in the throughflow region. *Abstracts in Eos*, 75(25Suppl.): 45.

Filloux, J. H. 1974. Electric field recording on the sea floor with short span instruments. *J. Geomagn. Geoelectr.*, 26: 269-279.

Filloux, J. H. 1987. Instrumentation and experimental methods for oceanic studies. In: J. A. Jacobs (ed.), Geomagnetism, Vol. 1, Academic Press, pp. 143-248.

Flierl, G. R., J. K. B. Bishop, D. M. Glover, and S. Paranjpe. 1992. Data management for JGOFS: theory and design. In: *Proceedings of the Ocean Climate Data Workshop*, February 18-21, 1992, Goddard Space Flight Center, Greenbelt, Maryland, U.S. NOAA and NASA publ. pp. 229-249.

Folland, C. K., T. N. Palmer, and D. E. Parker. 1986. Sahel rainfall and worldwide sea temperatures, 1901-85. *Nature*, 320: 602-607.

Folland C. K., T. R. Karl, and K. Ya. Vinnikov. 1990. Observed climate variations and change. In: Climate Change: The IPCC Scientific Assessment. J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, eds. Cambridge University Press, Cambridge, UK. pp. 195-238.

Folland, C. K., T. R. Karl, N. Nicholls, B. S. Nyenzi, D. E. Parker, and K. Ya Vinnikov. 1992. Observed climate variability and change. In: Climate Change, the Supplementary Report to the IPCC Scientific Assessment. J. T. Houghton, B. A. Callander, and S. K. Varney, eds. Meteorological Office, Bracknell, UK. pp. 135-170.

Fox, D. N., M. R. Carnes, and J. L. Mitchell. 1992. Characterizing major frontal systems: A nowcast/forecast system for the Northwest Atlantic. *Oceanography*, 5: 49-54.

Frankignoul, C. 1985. Sea surface temperature anomalies, planetary waves, and air-sea feedback in the middle latitudes. *Review of Geophysics*, 23(4): 357-390.

Frankignoul, C. 1991. Oceanic model testing. Proceedings, Aha Huliko'a, Hawaiian Winter Workshop, Honolulu, Hawaii. P. Muller and D. Henderson, eds. pp. 387-397.

Friis-Christensen, E. and K. Lassen. 1991. Length of the solar cycle: An indicator of solar activity closely associated with climate. *Science*, 254: 698-700.

Frouin, R., C. Gautier, and J. J. Morcette. 1988. Downward longwave irradiance at the ocean surface from satellite data. *J. Geophys. Res.*, 93: 597.

Frye, D. E., W. B. Owens, and J. R. Valdes. 1991. Ocean data telemetry: new methods for real-time ocean observation. *Oceanus*, 34: 46-52.

Fu, L.-L. and V. Zlotnicki. 1989. Observing oceanic mesoscale eddies from Geosat altimetry: preliminary results. *Geophys. Res. Letts.*, 16(5): 457-460.

Fu, F.-L., J. Vazquez, and M. E. Parke. 1987. Seasonal variability of the Gulf Stream system from satellite altimetry. *J. Geophys. Res.*, 92: 749-754.

Gaillard, F. 1994. Monitoring convection in the Gulf of Lion with tomography: a 3-D view. *EOS*, 75: 118.

Gandin, L. S. 1963. Objective Analysis of Meteorological Fields. Leningrad, Gidrometeorizdar, 266 pp. (reprinted in 1965 by the Israel program for Scientific Translations, Jerusalem, 238 pp.)

Garrett, C., R. Outerbridge, and K. Thompson. 1993. Interannual Variability in the Mediterranean buoyancy fluxes. *J.Climate*, 6(5): 900-910.

Gascard, J. C. 1973. Vertical motions in the region of deep water formation. *Deep-Sea Res.*, 29: 1011-1028.

Gascard, J. C. 1978. Mediterranean deep water formation, baroclinic instability and oceanic eddies. *Oceanol. Acta*, 1(3): 315-330.

Gates, W. L. 1987. Problems and prospects in climate modeling. In: Toward Understanding Climate Change, Westview Press, Boulder, CO. pp. 5-33.
Gautier, C., G. Diak, and S. Mase. 1980. A simple physical model to estimate incident solar radiation at the surface from GOES satellite data. *J. Appl. Met.*, 219: 1005-1012.
GCOS. 1993. Draft plan for the Global Climate Observing System (GCOS). Edited by the Chairman, Joint Scientific and Technical Committee for GCOS. Published GCOS Joint Project Office, Geneva. 36 pp.
GCOS Data Management Task Team (DMTT). 1994. Global Climate Observing System Initial Operational System, Data Management Plan (Second Draft). 38 pp.
Gill, A. E. and E. M. Rasmusson. 1983. The 1983-83 climate anomaly in the equatorial Pacific. *Nature*, 305: 229-234.
Gill, A. E. and P. P. Niiler. 1973. The theory of seasonal variability in the oceans. *Deep-Sea Res.*, 20: 141-177.
Gilman, C. and C. Garrett. 1994. Heat flux parameterizations for the Mediterranean Sea: The role of atmospheric aerosols and constraints from the water budget. *J. Geophys. Res.*, 99(C3): 5119-5134.
Glantz, M. H. 1984. Floods, fires, and famine: Is El Niño to blame? *Oceanus*, 27: 14-20.
Gloerson, P, W. J. Campbell, D. J. Cavalieri, J. C. Comiso, C. L. Parkinson, and H. J. Zwally. 1992. Arctic and Antarctic Sea Ice, 1978-1987; Satellite Passive Microwave Observations and Analysis, NASA SP-511, National Aeronautices and Space Administration, Washington, DC. 290 pp.
Gloerson, P. and W. J. Campbell. 1988. Variations in the Arctic, Antarctic and global sea ice cover during 1978-1987 as observed with Nimbus-7 SMMR. *J. Geophys. Res.*, 93(C9): 10,666-10,740.
GLOSS. 1990. Global Sea Level Observing System (GLOSS) Implementation Plan. Intergovernmental Oceanographic Commission Technical series, No. 35. Unesco, Paris, France. 90 pp.
Godfrey, J. S., A. Alexiou, A. G. Ilahude, D. M. Legler, M. E. Luther, J. P. McCreary, Jr., G. A. Meyers, K. Mizumo, R. R. Rao, S. R. Shetye, J. H. Toole, and S. Wacongne. 1995. The Role of the Indian Ocean in the Global Climate System: Recommendations Regarding the Global Ocean Observing System. Report of the Ocean Observing System Development Panel, Texas A&M University, College Station, TX, U.S.A. 89 pp.
Goodberlet, M. A., C. T. Swift, and J. C. Wilkerson. 1989. Remote sensing of ocean surface winds the special sensor microwave/imager. *J. Geophys. Res.*, 94(C10): 14, 547-14,555.
Gordon, A. L. 1981. Seasonality of the Southern Ocean sea ice. *J. Geophys. Res.*, 86: 4193-4197.
Gordon, A. L. and W. F. Haxby. 1990. Agulhas eddies invade the South Atlantic: Evidence from Geosat altimeter and shipboard conductivity-temperature-depth survey. *J. Geophys. Res.*, 95: 3117-3128.
Gray, W. M., C. W. Landsea, P. Mielke, and K. Berry. 1993. Predicting Atlantic seasonal hurricane activity 6-11 months in advance. *Weather and Forecasting*, 7: 440-455.
Gregory, J. M. 1993. Sea level changes under increasing atmospheric CO2 in a transient coupled ocean-atmosphere GCM experiement. Meteorological Office Climate Research Technical Note 42, U.K. Meteorological Office, Bracknell.
Guiffrida, M. R. 1985. Estimates of net ACC transports and Southern Ocean budgets of mass, heat, freshwater, oxygen and nutrients. M.S. Thesis, Texas A&M University, 85 pp.
Gulev, S. K. 1994. Long-term variability of air-sea interaction in the North Atlantic Ocean. Technical report, Institut für Meereskunde, Kiel, Germany.
Gupta, S. K., W. L. Darnell, and A. C. Wilber. 1992. A parameterization for longwave surface radiation from satellite data: recent improvements. *J. Appl. Meteor.*, 31(12): 1361.
Hall, M. M. and H. L. Bryden. 1982. Direct estimates and mechanisms of ocean heat transport. *Deep-Sea Res.*, 29: 339-359.

Halliwell, G. R., Jr. and P. Cornillon. 1989. Large-scale SST anomalies associated with subtropical fronts in the western North Atlantic during FASINEX. *J. Mar. Res.*, 47(4): 757-775.

Halpern, D. 1988. On the accuracy of monthly mean wind speeds over the equatorial Pacific. *J. Atmos. Ocean. Tech.*, 5: 362-367.

Halpern, D., R. A. Knox, and D. Luther. 1988. Observations of 20-day period meridional current oscillating in the upper ocean along the Pacific equator. *J. Phys. Oceanogr.*, 18: 1514-1534.

Halpert, M. S. and C. F. Ropelewski. 1992. Surface temperature patterns associated with the Southern Oscillation. *J. Climate*, 5: 577-593.

Hanawa, K., P. Rual, R. Bailey, A. Sy, and M. Szabados. 1994. Revised depth-time equation for Sippican or TSK T7, T6 and T4 expendable bathythermographs (XBT's). UNESCO Technical Paper, Marine Science 67.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner. 1984. Climate sensitivity: analysis of feedback mechanisms. In: Climate Processes and Climate Sensitivity, Geophysical Monograph Series, Vol. 29, ed. by J. E. Hansen and T. Takahashi, AGU, Washington, D. C. pp. 130-163.

Hanson, K., G. A. Maul, and T. R. Karl. 1989. Are atmospheric greenhouse effects apparent in the climatic record of the contiguous U.S., 1895-1987? *Geophys. Res. Letters*, 16: 49-52.

Harrison, D. E., W. S. Kessler, and B. S. Giese. 1989. Ocean circulation model hindcasts of the 1982-83 El Nino: Thermal variability along the ship-of-opportunity tracks. *J. Phys. Oceanogr.*, 19: 397-418.

Hastenrath, S. and L. Greischar. 1991. The monsoonal current regimes of the tropical Indian Ocean: observed surface flow fields and their geostrophic and wind-driven components. *J. Geophys. Res.*, 96(C7): 12,619-12,633.

Hayes, S. P., M. J. McPhaden, and A. Leetmaa. 1989. Observational verification of a quasi real time simulation of the tropical Pacific Ocean. *J. Geophys. Res.*, 94 (C2): 2147-2157.

Hayes, S. P., L. J. Mangum, J. Picaut, A. Sumi, and K. Takeuchi. 1991. TOGA TAO: A moored array for real-time measurements in the tropical Pacific Ocean. *Bull. Am. Met. Soc.*, 72: 339-347.

Heimann, M. 1991. Presentation at NATO Advanced Study Institute, Contemporary Global Carbon Cycle. Il Ciocco, Italy, September 8-20, 1991.

Hendry, R. M. 1982. On the structure of the deep Gulf Stream. *J. Mar. Res.*, 40(1): 119-142.

Huang, R. X. and R. W. Schmitt. 1993. The Goldsbrough-Stommel circulation of the world oceans. *J. Phys. Oceanogr.*, 23: 1277-1284.

International TOGA Project Office (ITPO). 1990. TOGA International Implementation Plan, Report No. 1 of the ITPO, 3rd Edition, WMO, Geneva.

IOC. 1991. Global Ocean Observing Systems Workshop Report. September 10-12, 1990, Alexandria, Virginia. Joint Oceanographic Institutions, Incorporated, Washington, D.C., 115 pp.

IOC. 1993. Global Ocean Observing System (GOOS): The Approach to GOOS. IOC-XVII/8 Annex 2 rev., Paris, 12 March 1993. 10 pp.

IPCC. 1990. Climate Change: The IPCC Scientific Assessment. J. T. Houghton, G. J. Jenkins, and J. J. Ephraums, eds. Cambridge University Press, Cambridge, UK. 365 pp.

IPCC. 1992. Climate Change, the Supplementary Report to the IPCC Scientific Assessment. J. T. Houghton, B. A. Callendar, and S. K. Varney, eds. Cambridge University Press, Cambridge, U.K. 200 pp.

Isemer, H. J. and L. Hasse. 1987. The Bunker Climate Atlas of the North Atlantic Ocean, Vol. 2. Springer-Verlag. 252 pp.

Isemer, H. J., J. Willebrand, and L. Hasse. 1989. Fine adjustment of large-scale air-sea energy flux paramerizations by direct estimates of ocean heat transport. *J. Climate*, 2: 1173-1184.

Jaeger, L. 1976. Monatskarten des Niederschlags dur dies ganze Erde, Berichte Deutsches Wetterdienstes, Nr. 139, Offenbach, 38 pp.

Janowiak, J. E. and P. A. Arkin. 1991. Rainfall variations in the tropics during 1986-1989 as estimated from observations of cloud-top temperature. *J. Geophys. Res.*, 96: 3359-3373.

Janssen, P. A. E. M. 1989. Wind-induced stress and the drag of air flow over sea waves. *J. Phys. Oceanogr.*, 19: 745-754.
Ji, M., A. Kumar, and A. Leetmaa. 1994a. A Multiseason Climate Forecast System at the National Meteorological Center. *Bull. Am. Met. Soc.*, 75(4): 569-577.
Ji, M., A. Leetmaa, and J. Derber. 1994b. An ocean analysis system for seasonal to interannual climate studies. *Mon. Wea. Rev.*, in press.
Josey, S. A., E. C. Kent, and P. K. Taylor. 1994. Seasonal variations between sampling and classical mean turbulent heat flux estimates in the North Atlantic. *Annales Geophysicae*, submitted.
Karl, T. R., J. D. Tarpley, R. G. Quayle, H. F. Diaz, D. A. Robinson, and R. S. Bradley. 1989. The recent climate record: what it can and cannot tell us. *Rev. Geophys.*, 27: 405-430.
Karl, T. R., R. W. Knight, and J. R. Christy. 1994. Global and hemispheric temperature trans: uncertainties related to inadequate spatial sampling. *J. Climate*, 7: 1144-1167.
Katsaros, K. B. 1990. Parameterization schemes and models for estimating the surface radiation budget. Surface Waves and Fluxes, Vol. 2, Remote Sensing. G. L. Geernaert and W. J. Plant (eds). Kluwer Academic Publishers, pp. 339-368.
Kawase, M. 1993. Effects of a concave bottom geometry on the upwelling driven circulating in an abyssal ocean basin. *J. Phys. Ocean.*, 23(2): 400-405.
Keeling, C. D., S. C. Piper, and M. Heimann. 1989. A three-dimensional model of atmospheric $CO_2$ transport based on observed winds. 4: Mean annual gradients and interannual variations. In: Aspects of Climate Variability in the Pacific and Western Americas. D. H. Peterson, ed. Geophysical Monograph 55, American Geophysical Union, Washington, D.C., USA, pp. 305-363.
Keigwin, L., G. A. Jones, and S. J. Lehman. 1991. Deglacial meltwater discharge, North Atlantic deep circulation, and abrupt climate change. *J. Geophys. Res.*, 96(C9): 16,811-16,826.
Kelly, K. A. and M. J. Caruso. 1990. A modified objective mapping technique for scatterometer wind data. *J. Geophys. Res.*, 95(C8): 13,483-13,496.
Kent, E. C. and P. K. Taylor. 1991. A catalogue of the Voluntary Observing Ships participating in the VSOP-NA. Marine Meteorology and Related Activities Report No. 25, World Meteorological Organization, Geneva.
Kent, E. C., B. S. Truscott, P. K. Taylor, and J. S. Hopkins. 1991. The accuracy of ship's meteorological observations: Results of the VSOP-NA. Marine Meteorology and Related Activities Report No. 26, World Meteorological Organization, Geneva.
Kent, E. C., P. K. Taylor, B. S. Truscott, and J. A. Hopkins. 1993. The accuracy of Voluntary Observing Ship's Meteorological Observations. *J. Atmos. and Ocean. Tech.*, 10(4): 591-608.
Kerr, R. A. 1991. Could the sun be warming the climate? *Science*, 254: 652-653.
Kerr, R. A. 1992. A successful forecast of an El Niño winter. *Science*, 255: 402.
Kessler, W. S. and B. A. Taft. 1987. Dynamic heights and zonal geostrophic transports in the central tropical Pacific during 1979-84. *J. Phys. Oceanogr.*, 17: 97-122.
Kiehl, J. T. and B. P. Briegleb. 1993. The relative roles of sulfate aerosols and greenhouse gases in climate forcing. *Science*, 260: 311-314.
Killworth, P. D. 1983. Deep convection in the world ocean. *Rev. Geophys. Space Phys.*, 21: 1-26.
Kindle, J. C. and J. D. Thompson. 1989. The 26- and 50-day oscillations in the western Indian Ocean: model results. *J. Geophys. Res.*, 94(C4): 4721-4736.
Kindle, J. C., G. W. Heburn, and R. C. Rhodes. 1987. An estimate of the Pacific to Indian Ocean throughflow from a global numerical model. In: Further Progress in Equatorial Oceanography, E. Katz and J. Witte (eds). Nova University Press, Dania, FL. pp. 317-322.
Kleeman, R. 1993. On the Dependence of Hindcast Skill on Ocean Thermodynamics in a Coupled Ocean-Atmosphere Model. *J. Climate*, 6(11): 2012-2033.
Koblinsky, C. J., P. Gaspar, and G. Lagerloef (eds). 1992a. The future of spaceborne altimetry: Oceans and climate change. Joint Oceanographic Institutions Incorporated, Washington, D.C., 75 pp.

Koblinsky, C. J., R. S. Nerem, R. G. Williamson, and S. M. Kloso. 1992b. Global scale variations in sea surface topography determined from satellite altimetry, AGU Geophysical Monography 69: Sea Level Chnages - Determinations and Effects. *International Union of Geodesy and Geophysics*, 11: 155-165.

Kousky, V. E. and A. Leetmaa. 1989. The 1986-87 Pacific warm episode: evolution of oceanic and atmospheric anomaly fields. *J. Climate*, 2: 254-267.

Krasnow, R. (ed.) 1986. Policy Aspects of Climate Forecasting. Proceedings of a Seminar held in Washington, D.C., March 4, 1986. National Center for Food and Agriculture Policy, Resources for the Future, Washington, DC.

Kushnir, Y. 1994. Inter-decadal variations in North Atlantic sea surface temperature and associated atmospheric circulation. *J. Climate*, 7: 141-157.

Kushnir, Y. and I. M. Held. 1994. The wintertime general circulation model response to North Atlantic SST anomalies. Abstract of talk given at ACCP Principal Investigator's Meeting, Princeton, NJ. May 9 - 11, 1994.

Lacombe, H., P. Tchernia, and L. Gamberoni. 1985. Variable bottom water in the western Mediterranean basin. *Prog. Ocean.*, 14: 319-338.

Large, W. G. 1985. WOCE Global Air-Sea Interaction Fields. *World Ocean Circulation Experiment*, U.S. WOCE Technical Report No. 1. 36 pp.

Large, W. G. and J. A. Businger. 1988. A System for Remote Measurements of the Wind Stress over the Oceans. *J. Atmos. and Ocean. Tech.*, 5: 274-285.

Larsen, J. C. 1992. Transport and heat flux of the Florida Current at 27°N derived from cross-stream voltages and profiling data: theory and observations. *Phil. Trans. R. Soc. Lond. A.*, 338: 169-236.

Latif, M. and M. Flügel. 1991. An investigation of short-range predictability in the tropical Pacific. *J. Geophys. Res.*, 96: 2661-2673.

Latif, M., A. Sterl, E. Maier-Reimer, and M. M. Junge. 1993a. Climate variability in a coupled GCM. Part I: The tropical Pacific. *J. Climate*, 6(1): 5-21.

Latif, M., A. Sterl, E. Maier-Reimer, and M. M. Junge. 1993b. Structure and predictability of the El Niño/Southern Oscillation phenomenon. *J. Climate*, 6(4): 700-708.

Lau, K. M. and P. H. Chan. 1986. The 40-50 day oscillation and the El Niño/Southern Oscillation: a new perspective. *Bull. Am. Met. Soc.*, 67(5): 533-534.

Lau, K. M. and P. H. Chan. 1988. Intraseasonal and Interannual Variations of Tropicial Convection: A Possible Link between the 40-50 day Oscillation and ENSO. *J. Atmos. Sci.*, 45(3): 506-521.

Lau, K. M. and P. J. Sheu. 1991. Teleconnections in global rainfall anomalies: seasonal to interdecadal time scales. In: Teleconnections linking worldwide climate anomalies: scientific basis and societal impact. M. H. Glantz, R. W. Katz, and N. Nicholls (eds.), Cambridge University, New York.

Lazier, J. 1980. Oceanic conditions at ocean weather ship Bravo; 1964-1974. *Atmos-Ocean*, 18: 227-238.

Le Traon, P. Y. 1991. Time scales of mesoscale variability and their relationship with space scales in the North Atlantic. *J. Mars. Res.*, 49: 467-492.

Le Traon, P. Y., M. C. Rouquet, and C. Bossier. 1990. Spatial scales of mesoscale variability in the North Atlantic as deduced from Geosat data. *J. Geophys. Res.*, 95(C11): 20,267-20,285.

Leaman, K. D. and F. A. Schott. 1991. Hydrographic structure of the convective regime in the Gulf of Lyons: Winter 1987. *J. Phys. Oceanogr.*, 21: 573-596.

Ledwell, J. R., A. J. Watson, and C. S. Law. 1993. Evidence for slow mixing across the pycnocline from an open-ocean tracer release experiment. *Nature*, 364: 701-703.

Leetmaa, A. 1993. Surface fluxes inferred from an ocean analysis system. Workshop on the use of Sub-surface Thermal Data for Climate Studies, Brest, France, 13-16 September 1993, ITPO Report No. 9/WOCE Report No. 110/93, Geneva. pp. 37-38.

Legates, D. R. and C. J. Willmott. 1990. Mean seasonal and spatial variability in gauge-corrected, global precipitation. *Int. J. Climatology*, 10: 111-127.

Legeckis, R. 1977. Long waves in the eastern equatorial Pacific Ocean: A view from a geostationary satellite. *Science*, 197: 1179-1181.

Legeckis, R. and G. Reverdin. 1987. Long waves in the equatorial Atlantic during 1983. *J. Geophys. Res.*, 92(C3): 2835-2842.

Legler, D. 1991. Errors in 5-day mean surface wind and temperature conditions due to inadequate sampling. *J. Atmos. Ocean. Tech.*, 8(5): 705-712.

Levitus, S. 1982. Climatological Atlas of the World Ocean. NOAA Prof. Paper 13, 17 microfiche, U.S. Govt. Printing Office, Washington, D.C. 173 pp.

Levitus, S. 1984. Annual cycle of temperature and heat storage in the World Ocean. *J. Phys. Oceanogr.*, 14: 727-746.

Levitus, S. 1989a. Interpentadal variability of temperature and salinity at intermediate depths of the North Atlantic Ocean, 1970-1974 versus 1955-1959. *J. Geophys. Res.*, 94(C5): 6091-6131.

Levitus, S. 1989b. Interpentadal variability of salinity in the upper 150 m of the North Atlantic Ocean, 1970-1974 vs. 1955-1959. *J. Geophys Res.*, 94(C7): 9679-9685.

Levitus, S. 1989c. Interpentadal variability of temperature and salinity in the deep North Atlantic, 1970-1974 versus 1955-1959. *J. Geophys. Res.*, 94(C11): 16,125-16,131.

Levitus, S. 1990. Interpentadal variability of steric sea level and geopotential thickness of the North Atlantic Ocean, 1970-1974 vs. 1955-1959. *J. Geophys. Res.*, 95(C5): 5233-5238.

Li, Z., H. G. Leighton, and R. D. Cess. 1993. Surface net solar radiation estimated from satellite measurements: comparisons with tower observations. *J. Climate*, 6: 1764-1772.

Lie, H.-J. and M. Endoh. 1991. Seasonal and interannual variability in temperature of the upper layer of the northwest Pacific, 1964-1983. *J. Phys. Oceanogr.*, 21: 385-397.

Lindsay, R. and D. A. Rothrock. 1993. The calculation of surface temperature and albedo of Arctic sea ice from AVHRR. *Ann. Glaciol.*, 17: 391-397.

Liu, W. T. 1988. Moisture and latent heat flux variabilities in the tropical Pacific derived from satellite data. *J. Geophys. Res.*, 93: 6749-6760.

Liu, W. T. and P. P. Niiler. 1984. Determination of the monthly mean humidity in the atmospheric surface layer over oceans from satellite data. *J. Phys. Oceanogr.*, 14: 1452-1457.

Liu, Z. 1994. A simple model of the mass exchange between the Subtropical and Tropical Ocean. *J. Phys. Ocean.*, 24(6): 1153-1165.

Liu, Z., J. Pedlosky, D. Marshall, and T. Warncke. 1993. On the feedback of the Rhines-Young pool on the ventilated thermocline. *J. Phys. Ocean.*, 23(7): 1592-1596.

Locarnini, R. A. 1991. On the spreading of Weddell Sea Deep Water in the Southwestern Atlantic Ocean. M.S. Thesis, Department of Oceanography, Texas A&M University, 49 pp.

Lorenc, A. 1981. A global three-dimensional multivariate statistical interpolation scheme. *Mon. Wea. Rev.*, 109: 701-721.

Lukas, R. and E. Lindstrom. 1987. The mixed layer of the western equatorial Pacific Ocean. In: *Proceedings of the 'Aha Huliko'a Hawaiian Winter Workshop on the Dynamics of the Oceanic Surface Mixed Layer*, Honolulu, Hawaii. P. Muller and D. Henderson, eds., Hawaii Institute of Geophysics Special Publication, pp. 67-94.

Luyten, J. R., J. Pedlosky, and H. Stommel. 1982. The Ventilated Thermocline. *J. Phys. Oceanogr.*, 13: 292-309.

Madden, R. A. and P. R. Julian. 1972. Description of global scale circulation cells in the tropics with a 40-50 day period. *J. Atmos. Sci.*, 29: 1109-1123.

Maier-Reimer, E. and U. Mikolwajewicz. 1989. Experiments with an OGCM on the cause of the Younger Dryas. In: Oceanography, A. Ayala-Castenares, W. Wooster, and A. Yanez-Arancibiu (eds). UNAM Press, Mexico, pp. 87-100.

Malin, G., S. M. Turner, and P. S. Liss. 1992. Sulfur: the plankton/climate connection. *J. Phycol.*, 28: 590-597.

Manabe, S. and R. J. Stouffer. 1994. Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide. *J. Climate*, 7(1): 5-23.

Mantyla, A. W. and J. L. Reid, Jr. 1983. Abyssal characteristics of the World Ocean waters. *Deep-Sea Res.*, 30(8A): 805-833.

Marotzke, J. 1991. Influence of convective adjustment on the stability of the thermohaline circulation. *J. Phys. Oceanogr.*, 21: 903-907.
Masuda, K. 1988. Meridional heat transport by the atmospher and the ocean: analysis of FGGE data. *Tellus*, 40A: 285-302.
Masuzawa, J. 1969. Subtropical Mode Water. *Deep-Sea Res.*, 16: 463-472.
Matrai, P. A. and M. D. Keller. 1993. Dimethylsulfide in a large-scale coccolithophore bloom in the Gulf of Maine. *Cont. Shelf Res.*, 13: 831-843.
McCartney, M. S. 1977. Water mass renewal in the subantarctic zone. *Antarctic Journal of the United States*, XII(4): 54-56.
McCartney, M. S. 1982. The subtropical recirculation of Mode Waters. *J. Mar. Res.*, 40(Suppl): 427-464.
McCartney, M. S. and L. D. Talley. 1982. The Subpolar Mode Water of the North Atlantic Ocean. *J. Phys. Oceanogr.*, 12: 1169-1188.
McClain, E. G., W. G. Pichel, and C. C. Walton. 1985. Comparative performance of AVHRR-based multichannel sea surface temperatures. *J. Geophys. Res.*, 90: 11,587-11,601.
McCreary, J. P., Jr. 1976. Eastern tropical ocean response to changing wind systems: with application to El Niño. J. Phys. Oceanogr., 6: 632-645.
McCreary, J. P. and P. K. Kundu. 1989. A numerical investigation of sea surface temperature variability in the Arabian Sea. *J. Geophys. Res.*, 94: 16,097-16,114.
McGowen, J. and P. Wiebe. 1991. Existing Biogeochemical Time Series. In: *Global Ocean Observing Systems Workshop Report.* September 10-12, 1990, Alexandria, Virginia. Joint Oceanographic Institutions, Incorporated, 1775 Massachusetts Ave., N.W., Suite 800, Washington, D.C., pp. 71-80.
McPhaden, M. J. 1993. TOGA-TAO and the 1991-93 El Niño-Southern Oscillation event. *Oceanography*, 6: 36-44.
McPhaden, M. J. and S. P. Hayes. 1990. Variability in the eastern equatorial Pacific ocean during 1986-1988. *J. Geophys. Res.*, 95: 13,195-13,208.
McPhaden, M. J., H. P. Freitag, and A. J. Shephard. 1990. Moored salinity time series measurements at 0°, 140°W. *J. Atmos. Ocean. Tech.*, 7: 569-575.
McPhaden, M. J., F. Bahr, Y. du Penhoat, E. Firing, S. P. Hayes, P. P. Niiler, P. L. Richardson, and J. M. Toole. 1992. The response of the western equatorial Pacific Ocean to westerly wind bursts during November 1989-January 1990. *J. Geophys. Res.*, 97(C9): 14,289-14,303.
MEDOC Group. 1970. Observation of the formation of deep water in the Mediterranean. *Nature*, 227: 137-140.
Merlivat, L. and A. Vézina. 1992. Scientific Rationale for Recommending Long-Term Systematic Ocean Observations to Monitor the Uptake of $CO_2$ by the Ocean — Now and in the Future. CCCO-JSC Ocean Observing System Development Panel, Texas A&M University, College Station, TX. 24 pp.
Merlivat, L., L. Memery, and J. Boutin. 1993. Gas exchange at the air-sea interface. Present status. Case of $CO_2$. Fourth International conference on $CO_2$. 13-17 September 1993.
Meyers, G. 1982. Interannual variation in sea level near Truk Island: A bimodal seasonal cycle. *J. Phys. Oceanogr.*, 12: 1161-1168.
Meyers, G. and J.-R. Donguy. 1984. The North Equatorial Countercurrent and heat storage in the western Pacific Ocean during 1982-1983. *Nature*, 312: 258-260.
Meyers, G. and H. Phillips. 1992. TOGA XBT sampling strategy. *TOGA Notes*, No. 7, pp. 16-21.
Meyers, G., H. Phillips, N. Smith, and J. Sprintall. 1991. Space and time scales for optimal interpolation of temperature—Tropical Pacific Ocean. *Prog. Ocean.*, 28: 189-218.
Meyers, G., R. J. Bailey, and A. P. Worby. 1994. Volume transport of Indonesian throughflow. *Deep-Sea Res.*, accepted.
Michaud, R. and J. Derome. 1991. On the mean meridional transport of energy in the atmosphere and oceans as derived from six years of ECMWF analysis. *Tellus*, 43A: 1-14.

Miller, M. J., A. C. M. Beljaars, and T. N. Palmer. 1992. The sensitivity of the ECMWF model to parameterization of evaporation from the tropical oceans. *J. Climate*, 5: 418-434.
Minnett, P. J. 1990. The regional optimization of infrared measurements of sea surface temperature from space. *J. Geophys. Res.*, 95(C8): 13,497-13,510.
Mitchell, J. F. B. 1989. The "Greenhouse" effect and climate change. *Reviews of Geophysics*, 27: 115-139.
Molinari, R., M. McPhaden, and R. Weller. 1992. Space and time scales of the upper ocean. Working Document for the Panel on Near-Term Development of Operational Ocean Observations of the NRC Ocean Studies Board.
Morawitz, W. M. L., P. Sutton, P. F. Worcester, B. D. Cornuelle, J. Lynch, and R. Pawlowich. 1994. Evolution of the 3-dimensional temperature structure and heat content in the Greenland Sea during 1988-89 from tomographic measurements. *EOS*, 75:118.
Moritz, R. E. 1992. Sampling the temporal variability of sea ice. Draft distribution, *Report of the sea ice thickness workshop*. A. S. Thorndike, C. Parkinson, and D. A. Rothrock (eds). 11 pp.
Munk, W. H. and C. Wunsch. 1982. Observing the ocean in the 1990s. *Phil. Trans. of the Royal Society, A.*, 307: 439-464.
Munk, W. H. and A. M. G. Forbes. 1989. Global ocean warming: an acoustic measure? *J. Phys. Oceanogr.*, 19: 1765-1778.
Munk, W. H., R. C. Spindal, A. Baggeroer, and T. G. Birdsall. 1994. The Heard Island feasibility test. *J. Acoustic Soc. of Amer.*, in press.
Murphy, A. H. 1995. Socio-economic value of climate forecasts. Report PES-94-1 to Economics Group, Office of the Chief Scientist, NOAA. Prediction and Evaluation Systems, Corvallis, Oregon. 35 pp.
Mysak, L. A. and G. J. Mertz. 1984. A 40- to 60-day oscillation in the source region of the Somali Current during 1976. *J. Geophys. Res.*, 89: 711-715.
Mysak, L. A., D. K. Manak, and R. F. Marsden. 1990. Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901-1984 and their relation to an inter-decadal Arctic Climate cycle. *Climate Dynamics*, 5: 111-133.
Neelin, J. D. 1990. A Hybrid Coupled General Circulation Model for El Niño Studies. *J. Atmos. Sci.*, 47(5): 674-693.
Neelin, J. D., M. Latif, M. A. F. Allaart, M. A. Cane, U. Cubasch, W. L. Gates, P. R. Gent, M. Ghil, C. Gordon, N. C. Lau, G. A. Meehl, C. R. Mechoso, J. M. Obserhuber, S. G. H. Philander, P. S. Schopf, K. R. Sperber, A. Sterl, T. Tokioka, J. Tribbia, and S. E. Zebiak. 1992. Tropical air-sea interaction in general circulation models. *Climate Dyn.*, 7: 73-104.
Nicholls, N. 1985a. Impact of the Southern Oscillation on Australian crops. *J. Climatol.*, 5: 553-560.
Nicholls, N. 1985b. Predictability of interannual variations of Australian seasonal tropical cyclone activity. *Mon. Wea. Rev.*, 113: 1143-1149.
Niebauer, H. J. 1980. Sea ice and temperature variability in the Eastern Bering Sea and the relation to atmospheric fluctuation. *J. Geophys. Res.*, 85: 7507-7515.
Niebauer, H. J. 1988. Effects of El Niño-Southern Oscillation and North Pacific weather patterns on interannual variability in the subarctic Bering sea. *J. Geophys. Res.*, 93: 5051-5068.
Nitta, T. and S. Yamada. 1989. Recent warming of tropical sea surface temperature and its relationship to the northern hemisphere circulation. *J. Meteor. Soc. Japan*, 67: 375-383.
Nowlin, W. D., Jr. and J. M. Klinck. 1986. The Physics of the Antarctic Circumpolar Current. *Reviews of Geophysics*, 24(3): 469-491.
Nowlin, W. D., Jr., R. D. Pillsbury, and J. Bottero. 1981. Observations of kinetic energy levels in the Antarctic Circumpolar Current at Drake Passage. *Deep-Sea Res.*, 28: 1-17.
Nowlin, W. D., Jr., T. Whitworth III, and R. A. Locarnini. 1991. The Deep Western Boundary Current in the South Pacific Ocean. *Eos, Transactions AGU*, 75(51): 31.
NRC. 1983. Changing climate: Report of the carbon dioxide assessment panel, a report of the Board of Atmospheric Sciences and Climate of the National Research Council. W. Nierenberg, ed. Washington D.C., National Academy Press.

NRC. 1994. Ocean-Atmosphere Observations Supporting Short-term Climate Predictions. Panel on Near-Term Development of Operational Ocean Observations, National Academy Press, Washington, DC. 31 pp.

O'Brien, J. J. (ed.) 1992. Workshop on the economic impact of ENSO forecasts on the American, Australian, and Asian continents. Florida State University, 85 pp.

Oberhuber, J. M. 1988. An atlas based on the "COADS" data set: the budgets of heat, buoyancy and turbulent kinetic energy at the surface of the global ocean. Report No. 15, Max-Planck-Institut für Meteorologie, Hamburg, Germany.

Oort, A. H. and T. H. Vonder Haar. 1976. On the observed annual cycle in the ocean-atmosphere heat balance over the Northern Hemisphere. *J. Phys. Oceanogr.*, 6: 781-800.

Oort, A. H. and J. P. Peixoto. 1983. Global angular momentum and energy balance requirements from observations. *Advances in Geophysics*, 25: 355-490.

Orr, J. C. 1993. Accord between ocean models predicting uptake of anthropogenic $CO_2$. *Water, Air, and Soil Pollution*, 70: 465-481.

Overland, J. E. and C. H. Pease. 1982. Cyclonic climatology of the Bering sea and its relation to sea ice extent. *Mon. Wea. Rev.*, 110: 5-13.

Owens, W. B. 1991. A statistical description of the mean circulation and eddy variability in the northwestern Atlantic using SOFAR floats. *Prog. Ocean.*, 28(3): 257-259.

Palmer, T. N. and D. L. T. Anderson. 1993. Scientific assessment of the prospects for seasonal forecasting: a European perspective. Technical Report No. 70, European Centre for Medium Range Weather Forecasts, Reading, England, 54 pp.

Pan, Y.-H. and A. H. Oort. 1983. Global climate variations connected with sea surface temperature anomalies in the eastern Pacific Ocean for the 1958-1973 period. *Mon. Wea. Rev.*, 111: 12,144-12,158.

Parker, D. E. 1985. A comparison of bucket and non-bucket measurements of sea surface temperature. Unpublished manuscript.

Parkinson, C. L. 1990. The impact of the Siberian High and Aleutian Low on the sea-ice cover of the Sea of Okhotsk. *Ann. Glaciol.*, 14: 226-229.

Parkinson, C. L. 1991. Interannual variability of monthly Southern Ocean sea ice distribution, *J. Geophys. Res.*, 96: 4791-4801.

Parkinson, C. L. 1992. Interannual variability of the spatial distribution of sea ice in the north polar region. *J. Geophys. Res.*, 97: 5349-5363.

Parkinson, C. L., J. C. Comiso, H. J. Zwally, D. J. Cavalieri, P. Gloerson, and W. J. Campbell. 1987. Arctic sea ice, 1973-1976: Satellite Passive Microwave Observations, NASA SP489, 296 pp.

Parrilla, G., A. Lavin, H. Bryden, M. Garcia, and R. Millard. 1994. Rising temperatures in the subtropical North Atlantic Ocean over the past 35 years. *Nature*, 369: 48-51.

Pearcy, W. G. and A. Schoener. 1987. Changes in the marine bio coincident with the 1982-83 El Niño in the northeastern subartic Pacific Ocean. *J. Geophys. Res.*, 92: 14,417-14,428.

Pedlosky, J. 1992. On the baroclinic structure of the abyssal circulation. *J. Phys. Oceanogr.*, 22: 652-659.

Pedlosky, J. and D. C. Chapman. 1993. Baroclinic structure of the Abyssal Circulation and the role of meridional topography. *J. Phys. Oceanogr.*, 23: 979-991.

Peixoto, J. P. and A. H. Oort. 1983. The atmospheric branch of the hydrological cycle and climate. In: Variations in the Global Water Budget, A. Street (ed). Reidel, pp. 5-65.

Peloquin, R. A. 1992. The Navy Ocean Modeling and Prediction Program. *Oceanography*, 5: 4-8.

Peltier, W. R. and A. M. Tushingham. 1989. Global sea level rise and the greenhouse effect: Might they be related? *Science*, 244: 806-810.

Peterson, E. W. and L. Hasse. 1987. Did the Beaufort Scale or the Wind Climate Change? *J. Phys. Oceanogr.*, 17(7): 1071-1074.

Peterson, R. G. and T. K. Chereskin. 1994. First scientific use of the Fast Hydrographic Profiler. *WOCE Notes*, 6(3): 10-15.

Philander, S. G. 1986. Unusual conditions in the tropical Atlantic Ocean in 1984. *Nature*, 322: 236-238.

Philander, S. G. H. 1990. El Niño, La Niña, and the Southern Oscillation. Academic Press, Inc., New York. 293 pp.

Philander, S. G. H., D. Halpern, R. Legeckis, L. Miller, C.Paul, R. Watts, R. Weisberg, and M. Wimbush. 1985. Long waves in the equatorial Pacific Ocean. *Eos, Transactions AGU*, 66(14): 154.

Philander, S. G. H., R. C. Pacanowski, N.-C. Lau, and M. J. Nath. 1992. Simulation of ENSO with a global atmospheric GCM coupled to a high-resolution tropical Pacific Ocean GCM. *J. Climate*, 5: 308-329.

Phillips, H., R. Bailey, and G. Meyers. 1990. Design of an ocean temperature observing network in the seas north of Australia. CSIRO Marine Laboratories Report No. 211.

Phillips, L. D., C. R. Peterson, and T. W. Keelin. 1978. The value of improved forecasts of climate for agricultural decision-making. Final Report PR-77.7-44. Decisions and Designs, McLean, Virginia.

Picaut, J. and R. Tournier. 1991. Monitoring the 1979-85 equatorial Pacific current transports with expendable bathythermograph data. *J. Geophys. Res.*, 96(suppl): 3263-3277.

Picaut, J., A. J. Busalacchi, M. J. McPhaden, and B. Camusat. 1990. Validation of the geostrophic method for estimating zonal currents at the equator from GEOSAT altimeter data. *J. Geophys. Res.*, 95: 3015-3024.

Pickard, G. L. and W. J. Emery. 1990. Descriptive Physical Oceanography. 5th ed. Pergamon Press, Oxford. 320 pp.

Pickart, R. S. 1992. Water mass components of the North Atlantic deep western boundary current. *Deep-Sea Res.*, 39(9): 1553-1572.

Pillsbury, R. D., J. S. Bottero, E. A. Seifert, and D. C. Root. 1985. A compilation of observations from moored current meters. Vol XV: Current temperature and pressure collected near the Emperor Seamounts. June 1982-November 1983. Oregon State University Data Report, 118, 85-13, 116 pp.

Pinker, R. T. and I. Laszlo. 1991. Effects of spatial sampling of satellite data on derived surface solar irradiance. *Atmos-Ocean Tech.*, 8: 96-107.

Pinker, R. T. and I. Laszlo. 1992. Modeling surface solar irradiance for satellite applications on a global scale. *J. Appl. Meteor.*, 31: 194-211.

Pollard, R. T. and L. A. Regier. 1992. Vorticity and vertical circulation at an ocean front. *J. Phys. Oceanogr.*, 22: 609-625.

Potemra, J. T., M. E. Luther, and J. J. O'Brien. 1991. The seasonal circulation of the upper ocean in the Bay of Bengal. *J. Geophys. Res.*, 96(C7): 12,667-12,683.

Price, J. F., R. A. Weller, and R. Pinkel. 1986. Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling, and wind mixing. *J. Geophys. Res.*, 91(C7): 8411-8427.

Price, J. F., M. O. Baringer, R. Lueck, G. Johnson, I. Amber, G. Parrilla, A. Cantos, M. A. Kennelly, and T. Sanford. 1993. Mediterranean outfloow mixing and dynamics. *Science*, 259: 1277-1282.

Pullen, P. E., H. P. Frietag, and M. J. McPhaden. 1995. Correcting moored ADCP data for fish bias errors at 0°, 110°W, and 0°, 140°W from 1990 to 1993. NOAA Technical Memorandum, in press.

Queffeulou, P. 1991. Accuracy of wind measurements performed on buoys, ship, and island during the TOSCANE-2 Experiment. *Atmos-Ocean Tech.*, 8: 835-855.

Quinn, W. H., D. O. Zopf, K. S. Short, and R. T. W. Kuo Yang. 1978. Historical trends and statistics of the Southern Oscillation, El Niño, and Indonesian droughts. *Fish. Bull.*, 76: 663-678.

Rasmusson, E. M. and T. H. Carpenter. 1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, 110: 354-384.

Reed, R. K. 1977. On estimating solar insolation over the ocean. *J. Phys. Oceanogr.*, 7: 482-285.

Reid, J. L. 1978. On the mid-depth circulation and salinity field in the North Atlantic Ocean. *J. Geophys. Res.*, 83: 5063-5067.

Reid, J. L. 1979. On the contribution of the Mediterranean Sea outflow to the Norwegian-Greenland Sea. *Deep-Sea Res.*, 26: 1199-1223.
Reid, J. L., Jr., W. D. Nowlin, Jr., and W. C. Patzert. 1977. On the characteristics and circulation of the Southwestern Atlantic Ocean. *J. Geophys. Res.*, 7(1): 62-91.
Reverdin, G. and J. Luyten. 1986. Near-surface meanders in the equatorial Indian Ocean. *J. Phys. Oceanogr.*, 16: 1088-1100.
Reynolds, R. W. 1988. A real-time global sea surface temperature analysis. *J. Climate*, 1: 75-86.
Reynolds, R. W. and T. M. Smith. 1994. Improved global sea surface temperature analyses using optimum interpolation. *J. Climate*, 7: 929-948.
Richardson, P. L., G. L. Huford, R. Limeburner, and W. S. Brown. 1994. North Brazil Current retroflection eddies. *J. Geophys. Res.*, 99(C3): 5081-5093.
Rienecker, M. M. and C. N. K. Mooers. 1989. Mesoscale eddies, jets, and fronts off Point Arena, California, July 1986. *J. Geophys. Res.*, 94(C9): 12,555-12,569.
Rintoul, S. R. 1991. South Atlantic interbasin exchange. *J. Geophys. Res.*, 96: 2675-2692.
Robinson, A. R., M. A. Spall, L. J. Walstead, and W. G. Leslie. 1989a. Data assimilation and dynamical interpolation in GULFCAST experiments. *Dyn. Atmos. Oceans*, 13: 301-316.
Robinson, A. R., S. M. Glenn, M. A. Spall, L. J. Walstad, G. M. Gardiner, and W. G. Leslie. 1989b. Forecasting Gulf Stream meanders and rings. *Eos, Transactions AGU*, 70: 1464-1473.
Roemmich, D. 1990. Sea level and the thermal variability of the ocean. In: *Sea Level Change*, Report of the Panel on Sea Level Change, National Research Council, National Academy Press, Washington, DC, 234 pp.
Roemmich, D. and C. Wunsch. 1985. Two transatlantic sections: meridional circulation and heat flux in the subtropical North Atlantic Ocean. *Deep-Sea Res.*, 32(6A): 619-664.
Roemmich, D. and B. Cornuelle. 1990. Observing the fluctuations of gyre-scale ocean circulation: a study of the subtropical South Pacific. *J. Phys. Oceanogr.*, 20: 1919-1934.
Roemmich, D. and B. Cornuelle. 1993. How representative are individual hydrographic sections of the long-term behaviour of the oceans? In: *Workshop on the use of Sub-Surface Thermal Data for Climate Studies*, Brest, France (13-16 September 1993), ITPO Report No. 9 [WOCE Report No. 110/93], WMO, Geneva, pp. 22-24.
Ropelewski, C. F. and M. S. Halpert. 1986. North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Mon. Wea. Rev.*, 114: 2352-2362.
Ropelewski, C. F. and M. S. Halpert. 1987. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation (ENSO). *Mon. Wea. Rev.*, 115: 1606-1626.
Rossow, W. B. and R. A. Schiffer. 1991. ISCCP cloud data products. *Bull. American Met. Soc.*, 72(1): 2-20.
Royer, T. C. 1989. Upper ocean temperature variability in the northeast Pacific Ocean: Is it an indicator of global warming? *J. Geophys. Res.*, 94(C12): 18,175-18,183.
Sanford, T. B., A. D. Chave, D. S. Luther, C. S. Cox, J. H. Filloux, and J. C. Larsen. 1990. Motional Electromagnetic Methods and WOCE, Report from the Ad Hoc Motional Electromagnetic Measurements Group. U.S. WOCE Technical Report Number 3, U.S. WOCE Office, College Station, TX. 42 pp.
Sanford, T. B., J. H. Dunlap, J. Verrall, T. J. Osse, R. G. Drever, A. C. Bartlett, and M. D. Allison. 1993. The Electric Field Float (EFF) and it's Sea Test on R/V ENDEAVOR Cruise 230. APL/UW TR 9314, December 1993.
Sanford, T. B., R. G. Drever, and J. H. Dunlap. 1995a. Barotropic Ocean Velocity Observations from an Electric Field Float, a Modified RAFOS Float. In: Proceedings of the IEEE Fifth Working Conference on Current Measurement, Steven Anderson, Gerald Appell, and Albert J. Williams 3rd, eds., IEEE Catalog No. 95CH35734. pp. 163-168.
Sanford, T. B., R. G. Drever, J. H. Dunlap, and W. E. Johns. 1995b. Barotropic flows observd by the towed transport meter. In: Proceedings of the IEEE Fifth Working Conference on Current Measurement, Steven Anderson, Gerald Appell, and Albert J. Williams 3rd, eds., IEEE Catalog No. 95CH35734. pp. 24-29.

Sarachik, E. 1991. Initial Implementation Plan for the U.S. TOGA Program on Seasonal to Interannual Prediction. In: *Report of the Tenth Session of the JSC/CCCO TOGA Scientific Steering Group*, WCRP-64, WMO/TD-No. 441, Geneva.

Schluessel, P., H.-Y. Shin, W. J. Emery, and H. Grassel. 1987. Comparison of satellite-derived sea surface temperatures with in situ skin measurements. *J. Geophys. Res.*, 92(C3): 2859-2874.

Schluessel, P., W. J. Emery, H. Grassel, and T. Mammen. 1990. On the bulk-skin temperature difference and its impact on satellite remote sensing of sea surface temperature. *J. Geophys. Res.*, 95(C8): 13,341-13,356.

Schmitt, R. W. and K. Bryan. 1991. Mysteries of the Ocean Water Budget. *Summary Report*, 12th Session, Committee on Climate Changes and the Ocean, Woods Hole, June, 1991. Annex IV SCOR/IOC.

Schmitt, R. W. and S. E. Wijffels. 1993. The Role of the Oceans in the Global Water Cycle. In: Interaction Between Global Climate Subsystems. G. A. McBean and M. Hauler (eds.). Geophysical Monograph 75, American Geophysical Union. pp. 77-84.

Schmitt, R. W., P. S. Bogden, and C. E. Dorman. 1989. Evaporation minus precipitation and density fluxes for the North Atlantic. *J. Phys. Oceanogr.*, 19: 1208-1221.

Schmitz, W. J., Jr. 1978. Observations of the vertical distribution of low frequency energy in the western North Atlantic. *J. Mar. Res.*, 36: 295-310.

Schmitz, W. J. and M. S. McCartney. 1993. On the North Atlantic circulation. *Reviews of Geophysics*, 31(1): 29-49.

Schmitz, W. J., Jr., P. P. Niiler, and C. J. Koblinsky. 1987. Two year moored instrument results along 152°E. *J. Geophys. Res.*, 92(C10): 10,826-10,834.

Schopf, P. S. and M. J. Suarez. 1988. Vacillations in a coupled ocean-atmosphere model. *J. Atmos. Sci.*, 45: 549-566.

Schott, F. and K. D. Leaman. 1991. Observations with moored acoustic Doppler current profilers in the convection regime in the Golfe du Lion. *J. Phys. Oceanogr.*, 21: 558-574.

Schulz, J., P. Schlussel, and H. Grassl. 1993. Water vapour in the atmospheric boundary layer over oceans from SSM/I measurements. *Intl. J. of Remote Sensing*., 14(15): 2773-2789.

Scrimger, J. A., D. J. Evans, G. A. McBean, D. M. Farmer, and B. R. Kerman. 1987. Underwater noise due to rain, hail and snow. *J. Acous. Soc. Amer.*, 81: 79-86.

Seager, R. and M. B. Blumenthal. 1994. Modeling Tropical Pacific Sea Surface Temperature with Satellite-Derived Solar Radiative Forcing. *J. Climate*, 7(12): 1943-1957.

Seager, R., S. E. Zebiak, and M. A. Cane. 1988. A model of the tropical Pacific sea surface temperature climatology. *J. Geophys. Res.*, 93: 1265-1280.

Searle, B. 1992. Global Temperature and Salinity Pilot Project. In: *Proceedings of the Ocean Climate Data Workshop*, February 18-21, 1992, Goddard Space Flight Center, Greenbelt, Maryland, U.S. NOAA and NASA publ. pp. 97-108.

Servain, J., M. Séva, and P. Rual. 1990. Climatology comparison and long-term variations of sea surface temperature over the tropical Atlantic Ocean. *J. Geophys. Res.*, 95(C6): 9421-9431.

Shillington, F. A., W. T. Peterson, L. Hutchings, T. A. Probyn, H. N. Waldron, and J. J. Agenbag. 1990. A cool upwelling filament of Namibia, southwest Africa: preliminary measurements of physical and biological features. *Deep-Sea Res.*, 37(11): 1753-1772.

Siegenthaler, U. and J. L Sarmiento. 1993. Atmospheric carbon dioxide and the ocean. *Nature*, 365: 119-125.

Simonot, J. Y. and H. Le Treut. 1987. Surface heat fluxes from a numerical weather prediction system. *Climate Dyn.*, 2: 11-28.

Smith, N. R. 1993. Ocean modeling in a Global Ocean Observing System. *Rev. Geophys.*, 31: 281-317.

Smith, N. R. and G. D. Hess. 1993. A comparison of vertical eddy mixing parameterizations for equatorial ocean models. *J. Phys. Oceanogr.*, 23: 1823-1830.

Smith, N. R., J. E. Blomley, and G. Meyers. 1991. A univariate statistical interpolation scheme for subsurface thermal analyses in the tropical oceans. *Prog. Ocean.*, 28: 219-250.

Smith, S. D., R. D. Muensch, and C. E. Pease. 1990. Polynyas and leads: an overview of physical processes and environment. *J. Geophys. Res.*, 95: 9461-9479.
Soniera, G. 1994. Inmarsat and Beyond. *Mariners Weather Log*, Summer 1994: 24-27.
Sprintall, J. and G. Meyers. 1991. An optimal XBT sampling network for the eastern Pacific Ocean. *J. Geophys. Res.*, 96(C6): 10,539-10,552.
Sprintall, J. and M. J. McPhaden. 1994. Surface layer variations observed in multiyear time series measurements from the western equatorial Pacific. *J. Geophys. Res.*, 99(C1): 963-979.
Stammer, D. and C. W. Böning. 1992. Mesoscale variability in the Atlantic Ocean from Geosat altimetry and WOCE high resolution modelling. *J. Phys. Oceanogr.*, 22: 732-752.
Steffen, K. and A. Schweiger. 1991. NASA team algorithm for sea ice concentration retrieval from Defense Meteorological Satellite Program Special Sensor Microwave Imager: comparison with Landsat satellite imagery. *J. Geophys. Res.*, 96(C12): 21,971-21,987.
Stephens, G. L., G. C. Campbell, and T. H. Vonder Haar. 1981. Earth radiation budgets. *J. Geophys. Res.*, 86: 9739-9760.
Stockdale, T., D. Anderson, M. Davey, P. Delecluse, A. Kattenburg, Y. Kitamura, M. Latif, and T. Yamagata. 1993. Intercomparison of tropical ocean models. *World Climate Research Program Report WCRP-79*, WMO/TD No. 545, Geneva, Switzerland, 43 pp.
Stommel, H. 1957. A survey of ocean current theory. *Deep-Sea Res.*, 4: 149-184.
Stommel, H. 1972. Studies in Physical Oceanography. A. Gordon (ed.), Vol. 2. Gordon and Breach, New York.
Stommel, H. 1980. Asymmetry of interoceanic freshwater and heat fluxes. *Proc. Nat. Acad. Sci.*, 77(5): 2377-2381.
Stommel, H. 1989. The Slocum Mission. *Oceanography*, 2(1): 22-25.
Stommel, H. and A. B. Arons. 1960a. On the abyssal circulation of the world ocean. I. Stationary planetary flow patterns on a sphere. *Deep-Sea Res.*, 6: 140-154.
Stommel, H. and A. B. Arons. 1960b. On the abyssal circulation of the world ocean. II. An idealized model of the circulation pattern and amplitude in oceanic basins. *Deep-Sea Res.*, 6: 217-233.
Stouffer, R. J., S. Manabe, and K. Ya. Vinnikov. 1994. Model assessment of the role of natural variability in recent greenhouse gas warming. *Nature*, 367: 634-636.
Stramma, L., P. Cornillon, R. A. Weller, J. F. Price, and M. G. Briscoe. 1986. Large diurnal sea surface temperature variability: satellite and in situ measurements. *J. Phys. Oceanogr.*, 16(5): 827-837.
Sturges, W. 1987. Large-scale coherence of sea-level at very low frequencies. *J. Phys. Oceanogr.*, 17: 2084-2094.
Sverdrup, H. U., M. W. Johnson, and R. H. Fleming. 1942. The Oceans. Their physics, chemistry, and general biology. Prentice-Hall, Inc., Englewood Cliffs, N.J. pp. 143-146; 688-671.
Swift, J. 1984. Circulation of Denmark Strait and Iceland-Scotland overflow waters in the North Atlantic. *Deep Sea-Res.*, 31(11): 1339-1355.
Swift, J. H. and K. Aagaard. 1981. Seasonal transitions and water mass formation in the Iceland and Greenland Seas. *Deep-Sea Res.*, 28A: 1107-1129.
Swift, J. H., K. Aagaard, and S. A. Malmberg. 1980. The contribution of the Denmark Strait overflow to the deep North Atlantic. *Deep-Sea Res.*, 27A: 29-42.
Sy, A. 1991. XBT measurements. *WHP Operations and Methods, WOCE Operation Manual*, WOCE Report No. 68/91, July 1991, Woods Hole, Mass., USA, 19 pp.
Tachibana, Y. and G. Wakahama. 1990. Effect of the equatorial Pacific Ocean on interannual variability in the Okhotsk sea ice. *Proceedings of 5th Okhotsk Sea and Sea Ice Symposium*, Mobetsu. pp. 59-62.
Tai, C.-K. and W. B. White. 1990. Eddy variability in the Kuroshio extension as revealed by Geosat altimetry: Energy propagation away from the jet, Reynolds stress, and seasonal cycle. *J. Phys. Oceanogr.*, 20(11): 1761-1777.
Talley, L. D. 1984. Meridional heat transport in the Pacific Ocean. *J. Phys. Oceanogr.*, 14: 231-241.

Tans, P. P, I. Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric $CO_2$ budget. *Science*, 247: 1431-1438.
Tans, P. P., J. A. Berry, and R. F. Keeling. 1993. Oceanic $^{13}C/^{12}C$ observations: a new window on ocean $CO_2$ uptake. *Global Biogeochemical Cycles*, 7(2): 353-368.
Tate, P. M., I. S. F. Jones, and B. V. Hamon. 1989. Time and space scales of surface temperatures in the Tasman Sea, from satellite data. *Deep-Sea Res.*, 36(3): 419-430.
Taylor, A. H., A. J. Watson, M. Ainsworth, J. E. Robertson, and D. R. Turner. 1991. A modeling investigation of the role of phytoplankton in the balance of carbon at the surface of the North Atlantic. *Global Biogeochem. Cycles*, 5: 151-171.
Taylor, P. K. 1985. TOGA surface fluxes of sensible and latent heat by in situ measurement and microwave radiometry. TOGA meeting, SIO, LA Jolla, CA.
Thompson, J. C. 1976. Living With Climatic Change, Phase II. Proceedings of the Symposium held at Reston, Virginia, November 9-11, 1976. The Mitre Corporation, McLean, Virginia, September 1977.
Thompson, J. D., T. L. Townsend, A. Wallcraft, and W. J. Schmitz, Jr. 1992. Ocean prediction and the Atlantic basin: scientific issues and technical challenges. Oceanography, 5: 36-41.
Thompson, K. R. 1986. North Atlantic sea level and circulation. *Geophys.J. Royal Astro. Soc.*, 87: 15-32.
Thorndike, A. S., C. Parkinson, and D. A. Rothrock (eds). 1992. Report of the sea ice thickness workshop, 18-21 November 1991, New Carrollton, Maryland. *Informal report of the Polar Science Center*, Applied Physics Laboratory, Univ. of Washington, Seattle. 41 pp. + 4 appendices.
TOGA/WOCE XBT/XCTD Programme Planning Committee (TWXXPPC). 1993. Workshop on the use of Sub-Surface Thermal Data for Climate Studies, Brest, France, 13-16 September 1993, ITPO Report No. 9 [WOCE Report No. 110/93], WMO, Geneva. 60 pp.
Tomczak, M. and J. S. Godfrey. 1994. Regional Oceanography: An Introduction. Pergamon Press, Elsevier Science Ltd. Oxford, England. 422 pp.
Toole, J. M. 1993. On the meridional circulation of the Southern Hemisphere subtropical oceans. Fourth International Conference on Southern Hemisphere Meteorology and Oceanography. *AMS Preprint Volume*: 342-344.
Toole, J. M. and B. Warren. 1993. A hydrographic section across the subtropical South Indian Ocean. *Deep-Sea Res.*, 40(10): 1973-2020.
Travis, J. 1994. Dialing up undersea data—long distance. *Science*, 263: 1223-1224.
Trenberth, E. and A. Soloman. 1994. The global heat balance: heat transport in the atmosphere and ocean. *Climate Dynamics*, 10: 107-134.
Trenberth, K. E. 1991. General characteristics of El-Niño-Southern Oscillation. In: <u>Teleconnections linking worldwide climate anomalies: scientific basis and societal impact</u>. M. H. Glantz, R. W. Katz, and N. Nicholls (eds), Cambridge University, New York.
U.S. WOCE. 1993. U.S. Contribution to WOCE Core Proejct 1, The Program Design for the Indian Ocean, U.S. WOCE Office, College Station, Texas. 80 pp.
Umatani, S. and T. Yamagata. 1991. Response of the eastern tropical Pacific to meridional migration of the ITCZ: the generation of the Costa Rica dome. *J. Phys. Oceanogr.*, 21(2): 346-363.
Vagle, S., W. G. Large, and D. M. Farmer. 1991. An evaluation of the WOTAN technique of inferring oceanic winds from underwater ambient sound. *Atmos-Ocean Tech.*, 8: 576-595.
van Loon, H. 1967. The half-yearly oscillations in middle and high southern latitudes and the coreless winter. *J. Atmos. Sci.*, 24: 472-486.
von Storch, H., M. Latif, and J. Biercamp. 1989. Simulation of the Southern Oscillation in an atmospheric general circulation model. *Phil. Trans. Roy. Soc. London*, A 329: 179-188.
Vonder Haar, T. H. and A. H. Oort. 1973. New estimate of annual poleward energy transport by Northern Hemisphere oceans. *J. Phys. Oceanogr.*, 3: 169-172.
Wallace, D. W. R. 1995. Monitoring Global Ocean Carbon Inventories, Ocean Observing System Development Panel, Texas A&M University, College Station, TX. 54 pp.

Warren, B. A. 1973. Transpacific hydrographic sections at Lats. 43°S and 28°S: The SCORPIO Expedition—II. Deep Water. *Deep-Sea Res.*, 20(1): 9-38.
Warren, B. A. 1981. Deep circulation in the world ocean. In: Evolution of Physical Oceanography, B. A. Warren and C. Wunsch (eds). MIT Press, Cambridge, Massachusetts. pp. 6-41.
Warren, B. A. 1983. Why is no deep water formed in the North Pacific? *J. Mar. Res.*, 41: 327-347.
Watson, A. J., C. Robinson, J. E. Robinson, P. J. B. Williams, and M. J. R. Fasham. 1991. Spatial variability in the sink for atmospheric carbon dioxide in the North Atlantic. *Nature*, 350(6313): 50-53.
WCRP. 1986. Scientific Plan for the World Ocean Circulation Experiment. WCRP Publications Series No. 6, WMO/TD-No. 122. World Meteorological Organization, Geneva. 83 pp.
WCRP. 1988a. World Ocean Circulation Experiment Implementation Plan, Vol. 1. Detailed Requirements. WCRP-11, WMO/TD-No. 242. World Meteorological Organization, Geneva. 69 pp + 2 annexes.
WCRP. 1988b. World Ocean Experiment: Surface Velocity Programme Planning Committee, *Report of the First Meeting SVP-1 and TOGA Pan-Pacific surface current study*. NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami Florida, USA, 25-26 April 1988. WCRP-26, WMO/TD-No. 323. World Meteorological Organization, Geneva. 35 pp.
WCRP. 1988c. WOCE Core Project 1 Planning Meeting on The Global Description. Washington, D.C., 10-14 November 1988. WCRP-2, WMO/TD-No. 205. World Meteorological Organization, Geneva. 125 pp.
WCRP. 1989. WOCE Surface Flux Determinations - A Strategy for in situ measurements. *Report of the Working Group on in situ measurements for fluxes*, La Jolla, 27 Feb - 3 March 1989. WCRP-23, WMO/TD-No. 304, World Meteorological Organization, Geneva.
WCRP. 1992. Tropical Ocean and Global Atmosphere International Implementation Plan. International TOGA Project Office, Geneva, Switzerland, Publication ITPO-1. 73 pp.
Weaver, A. J. and E. S. Sarachik. 1991a. Evidence for decadal variability in an ocean general circulation model: an advective mechanism. *Atmos.-Ocean*, 29: 1197-1231.
Weaver, A. J. and E. S. Sarachik. 1991b. The role of mixed boundary conditions in numerical models of the ocean's climate. *J. Phys. Oceanogr.*, 21(9): 1470-1493.
Weaver, A. J. and T. M. C. Hughes. 1992. Stability and variability of the thermohaline circulation and its link to climate. In: Trends in Physical Oceanography, Research Trends Service, Vol. 1, Council of Scientific Research Integration, Trivandrum, India. pp. 15-70.
Weaver, A. J., E. S. Sarachik, and J. Marotzke. 1991. Internal low frequency variability of the ocean's thermohaline circulation. *Nature*, 353: 836-838.
Weaver, A. J., J. Marotzke, P. F. Cummins, and E. S. Sarachik. 1993. Stability and variability of the thermohaline circulation. *J. Phys. Oceanogr.*, 23: 39-60.
Webb, D. J., P. D. Killworth, A. C. Coward, and S. R. Thompson. 1991. The FRAM Atlas of the Southern Ocean. Natural Environmental Council, Swindon, U.K.
Webster, F. 1990. Data management for global ocean observing systems. *Global Ocean Observing Systems Workshop Report*. September 10-12, 1990, Alexandria, Virginia. Joint Oceanographic Institutions, Incorporated, 1775 Massachusetts Ave., N.W., Suite 800, Washington, D.C., pp 87-95.
Webster, F. 1992. The role of the World Data Centers in handling ocean climate data. *Proceedings of the Ocean Climate Data Workshop*, February 18-21, 1992, Goddard Space Flight Center, Greenbelt, Maryland, U.S. NOAA and NASA publ. pp. 65-73.
Webster, P. 1994. The role of hydrological processes in tropical ocean-atmosphere interactions. *Rev. Geophys.*, accepted.
Weisberg, R. H. 1984. Instability waves observed on the equator in the Atlantic during 1983. *Geophys. Res. Lett.*, 11(8): 753-756.
Weisberg, R. H. and A. M. Horrigan. 1981. Low frequency variability in the equatorial Atlantic. *J. Phys. Oceanogr.*, 11: 913-920.

Weisberg, R. H. and T. J. Weingartner. 1988. Instability waves in the equatorial Atlantic Ocean. *J. Phys. Oceanogr.*, 18(11): 1641-1657.
Weisberg, R. H., A. M. Horrigan, and C. Colin. 1979. Equatorially trapped Rossby-gravity wave propagation in the Gulf of Guinea. *J. Mar. Res.*, 37: 67-86.
Weller, R. and T. Dickey. 1992. Building collaboratories in oceanogrpahy. In "Towards a National Collaboratory", National Research Council.
Weller, R. A. and P. K. Taylor. 1993. Surface conditions and air-sea fluxes. *OOSDP Background Report #3.* CCCO-JSC Ocean Observing System Development Panel, Texas A&M University, College Station, Texas. 131 pp.
Weller, R. A., D. L. Rudnick, R. E. Payne, J. P. Dean, N. J. Pennington, and R. P. Trask. 1990. Measuring near-surface meteorology over the ocean from an array of surface moorings in the subtropical convergence zone. *Atmos.-Ocean. Tech.*, 7(1): 85-103.
Weller, R. A., D. L. Rudnick, C. C. Eriksen, K. L. Polzin, N. S. Oakey, J. W. Toole, R. W. Schmitt, and R. T. Pollard. 1991. Forced ocean response during the Frontal Air-Sea Interaction Experiment. *J. Geophys. Res.*, 96(C5): 8611-8638.
White, W. B. and R. C. Bernstein. 1979. Design of an oceanographic network in the midlatitude North Pacific. *J. Phys. Oceanogr.*, 13: 531-544.
White, W. B., G. Meyers, and K. Hasunuma. 1982. Space/time statistics of short-term climatic variability in the western North Pacific. *J. Geophys. Res.*, 87: 1979-1989.
White, W. B., G. Meyers, J. R. Donguy, and S. E. Pazan. 1985. Short-term climatic variability in the thermal strucutre of the Pacific Ocean during 1979-98. *J. Phys. Oceanogr.*, 15: 917-935.
Whitworth, T., III. 1983. Monitoring the transport of the ACC at Drake Passage. *J. Phys. Oceanogr.*, 13(11): 2045-2057.
Whitworth, T., III and R. G. Peterson. 1985. Volume transport of the ACC from bottom pressure measurements. *J. Phys. Oceanogr.*,15(6): 810-816.
Whitworth T., III, W. D. Nowlin, Jr., R. D. Pillsbury, M. I. Moore, and R. F. Weiss. 1991. Observations of the Antarctic Circumpolar Current and Deep Boundary Current in the Southwest Atlantic. *J. Geophys. Res.*, 96(C8): 15,105-15,118.
Wigley, T. M. L. and S. C. B. Raper. 1992. Implications for climate and sea level of revised IPCC emission scenarios. *Nature*, 357: 589-593.
Wijffels, S. E., R. W. Schmitt, H. L. Bryden, and A. Stigebrandt. 1992. Transport of Freshwater by the Oceans. *J. Phys. Oceanogr.*, 22(2): 155-162.
Wilkerson, J. C. and M. D. Earle. 1990. A study of differences between environmental reports by ships in the voluntary observing program. *J. Geophys. Res.*, 95(C3): 3373-3385.
Willebrand, J. 1993. Forcing the ocean by heat and freshwater fluxes. In: Energy and water cycles in the climate system, E. Raschke and D. Jacob (eds). Springer Verlag, pp. 215-234.
Wilson, J. R. 1992. The Global Ocean Observing System - one perspective. *Proceedings of the Ocean Climate Data Workshop*, February 18-21, 1992, Goddard Space Flight Center, Greenbelt, Maryland, U.S. NOAA and NASA publ. pp. 79-84.
WMO. 1991a. The Global Precipitation Climatology Project. *Report of the Fifth Session of the International Working Group on Data Management.* Laurel, Maryland, 20-21 May 1991. WCRP-60, WMO/TD No. 436. 21 pp + 5 appendices.
WMO. 1991b. Report of the Twelfth Session of the Joint Scientific Committee. Bremen, Germany, 18-23 March 1991. WMO/TD No. 432. 100 pp.
WOCE. 1993. The WOCE Upper Ocean Thermal Data Assembly Centre Coordination Group, Report of the Fourth meeting (UOT/DAC-IV), Hobart, Tasmania, April 1993, WOCE Report No. 106/93, WOCE IPO, Wormley.
WOCE. 1994a. Report of the 8th Meeting (NEG-8) and Workshop on Ocean Models for Climate Research. WOCE Numerical Experimentation Group, WOCE Report No. 117/94, Institute of Ocean Sciences, Vancouver Island, Canada, 13-15 September 1993.
WOCE. 1994b. WOCE Strategy for Ocean Modeling. Science Plan for Ocean Modeling, WOCE Numerical Experimentation Group, WOCE Report No. 112/94, WOCE International Project Office, Wormley, UK.

WOCE. 1994c. The WOCE Handbook: A Guide to WOCE Scientific Infrastructure for 1994. WOCE International Project Office, WOCE Report 118/94, 42 pp.
Woodruff, S. D., R. J. Slutz, R. L. Jenne, and P. M. Steurer. 1987. A comprehensive ocean-atmosphere data set. *Bull. Amer. Meteor. Soc.*, 68: 1239-1249.
Worthington, L. V. 1959. The 18° water in the Sargasso Sea. *Deep-Sea Res.*, 5: 297-305.
Worthington, L. V. 1976. On the North Atlantic circulation. The Johns Hopkins Oceanographic Studies No. 6. The Johns Hopkins University Press, Baltimore. 110 pp.
Wunsch, C. 1991a. Global-scale sea surface topography from combined altimetric and tide gauge measurements. *J. Geophys. Res.*, 96: 15,053-15,082.
Wunsch, C. 1991b. Large-scale response of the ocean to atmospheric forcing at low frequencies. *J. Geophys. Res.*, 96: 15,083-15,092.
Wunsch, C., D. Hu, and B. Grant. 1983. Mass, heat, salt and nutrient fluxes in the South Pacific Ocean. *J. Phys. Oceanogr.*, 13: 725-753.
Wyrtki, K. 1979. Sea level variations: monitoring the breath of the Pacific. *Eos, Trans. AGU*, 60: 25-27.
Wyrtki, K. 1984. The slope of sea level along the equator during the 1982-1983 El Niño. *J. Geophys. Res.*, 89: 10,419-10,424.
Wyrtki, K. 1987. Indonesian throughflow and the associated pressure gradient. *J. Geophys. Res.*, 92: 12,941-12,946.
Wyrtki, K., B. J. Kilonsky, and S. Nakahara. 1988. The IGOSS Sea Level Pilot Project in the Pacific. Technical Report, JIMAR contribution. 88-0150, Data Report 003, Joint Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii, 59 pp.
Yamagata, T. 1991. Asian monsoon and ocean circulation in the west Pacific. Annex III of Summary Report of the Twelfth Session of the Committee on Climatic Changes and the Ocean, SCOR-IOC/CCC)-XII/3.
Yasunari, T. 1991. Monsoon and ENSO: a coupled ocean/land/atmosphere system. *TOGA Notes*, 2: 9-13.
Yelland, M. J., P. K. Taylor, I. E. Consterdine, and M. H. Smith. 1994. The use of the inertial dissipation technique for shipboard wind stress determination. *J. Atmos. Ocean Tech.*, accepted.
Yoo, J.-M. and J. A. Carton. 1990. Annual and interannual variation of the freshwater budget in the tropical Atlantic Ocean and the Caribbean Sea. *J. Phys. Oceanogr.*, 20(6): 831-845.
Zebiak, S. E. 1993. Air-sea interaction in the equatorial Atlantic region. *J. Climate*, 6: 1567-1586.
Zebiak, S. E. and M. A. Cane. 1987. A model El Niño–Southern Oscillation. *Mon. Wea. Rev.*, 115: 2262-2278.
Zhao, Y. P. and G. A. McBean. 1986. Annual and interannual variability of the North Pacific ocean-to-atmosphere total heat transfer. *Atmos.-Ocean*, 24(3): 283-291.
Zlotnicki, V., L.-L. Fu, and W. Patzert. 1989. Seasonal variability in global sea level observed with Geosat altimetry. *J. Geophys. Res.*, 94(C12): 17,959-17,970.

## ANNEX I: Terms of Reference for the OOSDP

i) To formulate the conceptual design of a long-term, systematic observing system to monitor, describe, and understand the physical and biogeochemical processes that determine ocean circulation and the effects of the ocean on seasonal to decadal climate changes and to provide the observations needed for climate predictions,

ii) To cooperate as appropriate with the planners of other scientific or operational programs related to climatic change and to collate relevant data requirements and observing system specifications, and

iii) To liaise with responsible scientific institutions and agencies, including environmental administrations and space agencies, to attempt to ensure the compatibility of the proposed global ocean observing system development program with the long-term plans of these organizations.

## ANNEX II: Linkages to Existing Systems

The system design strategy of this report assumes the ocean observing system will, to the extent that it is practical, be built upon existing technology and existing systems—programs that have been launched to support services, climate, coastal, or fisheries needs. This annex describes the existing systems and their roles in the collection and dissemination of global data. To effectively link with these systems, plans for the ocean observing system must be implemented in close cooperation with key operational personnel in these systems, following closely developments in communications, data distribution and formats.

There are essentially three types of oceanographic data exchange within existing systems: operational, i.e. near-real-time, exchange of in situ and some satellite data through the WWW and IGOSS, primarily on the Global Telecommunications System; non-operational, i.e. delayed-mode, exchange through the IODE; and delayed-mode exchange of ocean satellite data, both operationally and non-operationally, by a variety of means. It must be recognized that individual ocean platforms may contribute to the operations of a number of existing systems. For example, a drifting buoy may be deployed as part of a particular research program; however, its data, if available on the GTS, will contribute to operational meteorology through the WWW, to operational oceanography through IGOSS, and eventually be archived through the IODE.

### A. World Weather Watch (WWW)

The WMO WWW is a coordinated world-wide system whose primary purpose is to make available, within the agreed system, meteorological and other environmental information required for the provision of meteorological services and for research. It is the only international operational program established to gather and distribute meteorological and related environmental data in real-time on a global scale. The WWW incorporates frequent and regular observations of a wide range of geophysical variables from thousands of locations on land, sea, and air as well as from satellites; rapid collection and exchange of the observational data; preparation of information in a variety of forms describing the current and forecast of atmospheric, hydrologic, and ocean surface conditions; and dissemination of this information.

1. The WWW objectives are:

a) To implement and operate by Members of the WWW a world-wide integrated system for the collection, processing, and rapid exchange of meteorological and related environmental data, analyses, and forecasts;
b) To make available, both in real-time and non-real-time, as appropriate, observational data, analyses, forecasts, and other products to meet the needs of all Members, of other WMO programs and of relevant programs of other international organizations; and
c) To arrange for the introduction of standard methods and technology which will enable Members to make the best use of the system and ensure an adequate level of services.

2. Core elements of the WWW

The *Global Observing System* consists of facilities and arrangements for making observations at stations on land and at sea, and from aircraft, satellites and other platforms. The surface-based sub-system is composed of regional basic synoptic networks, other meteorological observations, climatological stations, agricultural meteorological stations, and special stations. A network of VOS also participate. The space-based sub-system is composed of the near-polar-orbiting and geostationary meteorological satellites. At present, there are some 9500 stations on land, 7000 ships, 800 fixed and drifting buoys, 600 radar stations, 3000 aircraft, and a system of at least four orbiting and five geostationary satellites, all of which generate daily approximately 8 million characters of alpha-numeric data and contribute to the operation of the WWW.

The *Global Data Processing System* consists of World, Regional/Specialized and National Meteorological Centers to provide processed data, analyses, and forecast products.

The *GTS* is composed of an increasingly automated network of telecommunication facilities for the rapid, reliable collection and distribution of observational data and processed information. This GTS is an integrated system consisting of three levels: point-to-point circuits, meteorological telecommunication centers, and data distribution systems.

The capacity of the GTS, while not unlimited, is sufficient to meet most expected oceanographic requirements for in situ data exchange during the next decade. However, the GTS is a complex network of stations interconnected at different levels of technology. This often places severe limitations on the system. As one center updates its formats or equipment, other centers that relay the data, and subsequently those that have requested the data, may not have fully compatible software or transmission receipt capabilities, resulting in data transmission loss. In addition, the GTS presently operates on a "store and forward" basis, which is appropriate for operational data exchange, but not necessarily for oceanographic or climatological purposes. Work is now underway to develop a "GTS overlay", based on the request-response concept for data exchange, which is better adapted to oceanographic requirements.

The system as it presently stands consists of many diverse formats which may be used in the processing chain. Format conversion at the regional centers causes time delays, data loss, as well as programming and maintenance costs. It has been proposed that a common format for data management be developed. This would:

- reduce the need for format conversion,
- speed data flow,
- save original data and all changes made to the data as they are modified for quality control,
- save data that are now lost in the system, and
- require fewer software programs.

3. WWW support functions consist of:

a) WWW Data Management to coordinate, manage, and monitor the flow of data and products within the WWW system in accordance with international standards to assure their quality and timely delivery to meet Member's individual needs and those of other WMO programs; and

b) WWW System Support Activity to provide guidance, scientific and technical information, and training to those involved in the planning, development, and operation of WWW components; and to initiate, coordinate, and evaluate various WWW cooperative activities and support actions.

4. Ocean-specific sub-systems of the Global Observing System.

Voluntary Observing Ship Program

Voluntary Observing Ships collect and transmit, at standard synoptic hours, reports containing observations of some or all of the following parameters: surface barometric pressure, surface wind, surface air temperature, dewpoint, cloud amount and height, weather, SST, sea state, sea ice, and icing. Through conventional HF radio communications, 327 coastal stations accept ships' weather reports without charge to ships. Four INMARSAT Coast Earth Stations covering the Atlantic Ocean region, two covering the Indian Ocean region, and four others covering the Pacific Ocean region accept weather reports from ships equipped with Ship Earth Stations without charge to ships. About 40% of participating ships have such equipment. As a result of the implementation of the Global Maritime Distress and Safety System, virtually all ocean-going ships will be equipped with INMARSAT communications equipment by the end of this decade.

The number of Voluntary Observing Ships has been decreasing at the rate of about 2-4% per year due to the decrease in the number of transoceanic ships. WMO officials believe that it is not possible to increase the number of participating ships for this reason. Between 3000 and 4000 ships' weather reports are received daily at major WWW telecommunications and data processing centers. Ships have been recruited by 49 WMO members and are managed nationally through a network of Port Meteorological Officers.

Ocean Weather Ships

Two Ocean Weather Ships are presently operational as ocean stations: one operated by the UK normally at 59°N, 20°W, and one operated by Norway at 66°N, 2°E. They collect and transmit a full suite of surface and upper air meteorological observations, as well as surface and sub-surface oceanographic data. The long-term future of these platforms is uncertain.

Buoy Programs

More than 1100 drifting buoys have been deployed worldwide in support of a large number of programs, both research and operational. Of these, some 600 had their data distributed in real time on the GTS in early 1993, and contributed to both meteorology and oceanography. The location of the buoys and the collection of their data are carried out using the Argos system, based on the NOAA polar-orbiting satellites and operated by CLS/Service Argos (France). All the buoys reporting on the GTS carry at least SST sensors; around 150-200 have air pressure sensors; while a smaller number also carry sensors for air temperature and wind. Operational buoy programs, including data transmission, real-time quality control and GTS distribution aspects are coordinated globally by the Data Buoy Cooperation Panel (DBCP). A global archive for drifting buoy data is maintained by the Marine Environmental Data Service (Canada) as the RNODC (Drifting Buoys) of IODE, while Météo France is the IGOSS SOC for drifting buoys.

The Tropical Atmosphere Ocean (TAO) Array

The TOGA arrays in the Equatorial Pacific Ocean contribute a significant amount of operational and delayed-mode data. These arrays are complemented by drifting buoys, VOS/XBT measurements, and tide gauge measurements discussed elsewhere in this section. The TAO array measures surface wind, air temperature, SST, ten subsurface temperatures to a maximum depth of 500 meters, and two subsurface pressures. Some moorings also measure insolation, rainfall, salinity, and currents. Most data are telemetered to shore via the Argos System and recorded internally on magnetic tape cassette or solid state electronic memory. Winds, SST, and subsurface temperatures are transmitted through Argos for insertion on the GTS.

Satellite observations and satellite communications

Satellite observations, which began just over 30 years ago, have a special importance over the oceans. Currently polar orbiting satellites are operated by France, India, Japan, the USA, and the Russian Federation. Geostationary satellites are operated at different locations over the Equator: by the European Satellite Consortium (EUMETSAT/ESA) – 0°E, India – 74°E, Japan – 140°E, and the USA – 75°W and 135°W. Each of these satellites carries a variety of sensors allowing estimation of sea surface temperature, air temperature, and cloud temperature. In addition to transmitting imaging data in the visible and infra-red bands, these provide a substantial capacity for data relay of surface observations.

Neither GOES nor Argos is ideal for oceanographic data relay. GOES has a limited area coverage. Argos is global in coverage but can handle only messages of 256 bits or less. More importantly, neither GOES nor Argos supports two-way communications. Two-way communications are required to receive observations from ships and in return, to relay data and products back to the ships.

The INMARSAT-A system was designed for two-way global voice and telex communications and is installed on over 5000 ships. Although INMARSAT-A has great potential for use in IGOSS and the WWW, it has not been more widely used for marine environmental data, partly because of a lack of international agreement on cost sharing. There are agreements for funding coastal radio stations but not for global satellite systems. The countries where INMARSAT-A ground stations are located at present pay virtually all the costs of global environmental data reporting through INMARSAT.

B. The Integrated Global Ocean Services System (IGOSS)

1. Functions.

IGOSS is the operational network for the global collection and exchange of ocean data, products, and services. IGOSS was established in 1967 jointly by the IOC and the WMO. The purpose of IGOSS is to make available to Member States data and information required to provide efficient and effective ocean services for both operational and research applications. IGOSS promotes, coordinates, and develops the international arrangements necessary for the timely acquisition and exchange of data, the provision of services, and the dissemination of products in the form of observations, analyses, and forecasts. IGOSS deals only with near-real-time or "operational" data, i.e. data exchanged internationally within 30 days of observation time. IGOSS serves marine weather forecasting, fisheries research, commercial fishing, navigation, and pollution control as well as climate-related studies.

2. IGOSS structure.

IGOSS consists of the facilities contributed by participating countries for obtaining standardized oceanic observations from research ships, and voluntary observing ships, tide gauges, ocean weather stations, buoys, fixed platforms, satellites, and aircraft (see also the previous section on ocean specific sub-systems of the WWW). An important component of this system is the network of ships-of-opportunity. These are commercial vessels that take and transmit oceanographic observations including bathythermographic data, sea surface temperature, weather and current observations. The National Oceanographic Centers provide quality control, transmit data, and prepare products in accordance with national priorities. Specialized Oceanographic Centers collect and process data from the GTS and/or other sources, perform quality control, and prepare specified products. The World Oceanographic Centers receive data from the GTS, perform quality control, and prepare global products.

The IGOSS Telecommunications Arrangements consist of the facilities of the GTS and other arrangements such as the informal telemail transmission of data to centers. The National Meteorological Services responsible for the operation of telecommunication centers of the GTS are also responsible for both transmission to and reception from the GTS of IGOSS observational data and processed information.

The need for a flexible format for many types of oceanographic data has long been recognized by IGOSS. The WMO Commission for Basic Systems (CBS) has accepted this requirement and, using the IGOSS Flexible Code (IFC) as a basis, has

a) adopted the experimental use of SEALEV code for the transmission of sea level data on the GTS, and

b) authorized continuing work on a new universal flexible character code for FLEX, for the GTS transmission of both meteorological and oceanographic data. As part of its general upgrade of the GTS to handle more data and reduce data delays and errors, WMO has developed the Binary Universal Format for Data Representation (BUFR) for observation data.

3. Status of Present Activities and Future Plans.

The BATHY/TESAC component of IGOSS, launched in 1972, is now the major element of the IGOSS system. "BATHY" refers to temperature vs. depth profiles collected using XBT's or MBT's; the "TESAC" (Temperature, Salinity, Conductivity) portion constitutes measurements taken with Conductivity/Temperature/ Depth equipment. In 1992 a total of 45845 BATHY messages and 2962 TESAC messages were transmitted via the GTS; the daily average was 133 messages. Countries contributing the majority of these data were: Australia, Canada, China, France, Germany, Japan, the Russian Federation, United Kingdom, and USA. Figure AII-1 indicates the number of subsurface temperature (BATHY) and salinity (TESAC) measurements that were exchanged via the GTS for the period of 1985 through 1992.

In 1989 approximately 200 ships (both research and merchant) from 23 countries contributed to the collection of IGOSS data. Many of these ships carried XBT systems which receive, store, and transmit data accurately and quickly. They can electronically digitize XBT profiles and encode messages for satellite transmission. These systems are modular, small in size, and can be easily installed and removed from ships.

Recently standard track lines have been established. Using these lines as a guide for the required sampling areas, Member State commitments are needed for provision of ships, equipment, and XBT probes. The IGOSS Plan and Implementation Program (1989-1995) calls for equipping 500 ships with automatic data formatting and reporting systems which will report both subsurface temperature and ship drift current observations via satellite to National centers and then to the GTS.

In addition to projects for sea level and subsurface temperature products, IOC and WMO in 1989 established an IGOSS-IODE Global Temperature-Salinity Pilot Project to demonstrate the IGOSS-IODE end-to-end data management capability. Additional priorities for IGOSS include increasing attention to quality control; a Task Team was established in 1989 to review quality control procedures for automated systems. Standardization is also important to facilitate the exchange of data. The feasibility of establishing a similar pilot project for current measurements to promote, improve, and standardize current data is being studied.

C. Global Sea Level Observing System (GLOSS)

1. Functions.

The GLOSS is an international system, coordinated by IOC, to provide high-quality standardized sea level data from a global network of sea level stations. Seventy-nine countries participate in GLOSS and have designated national GLOSS contacts. Regional GLOSS coordinators have also been designated by IOC regional bodies.

2. Status of Present Activities and Future Plans.

The GLOSS Implementation Plan provides a planned global network of 300 permanent sea-level stations for obtaining standardized sea level observations. This forms the primary framework to which regional and national sea-level networks can be related. About two-thirds of the GLOSS stations are operational. Establishment and/or upgrading of about 100 additional conventional tide-gauges is required to achieve full global network. Particular efforts are required to install and maintain GLOSS stations in the Arctic Ocean and the Southern Ocean. Part of the GLOSS network

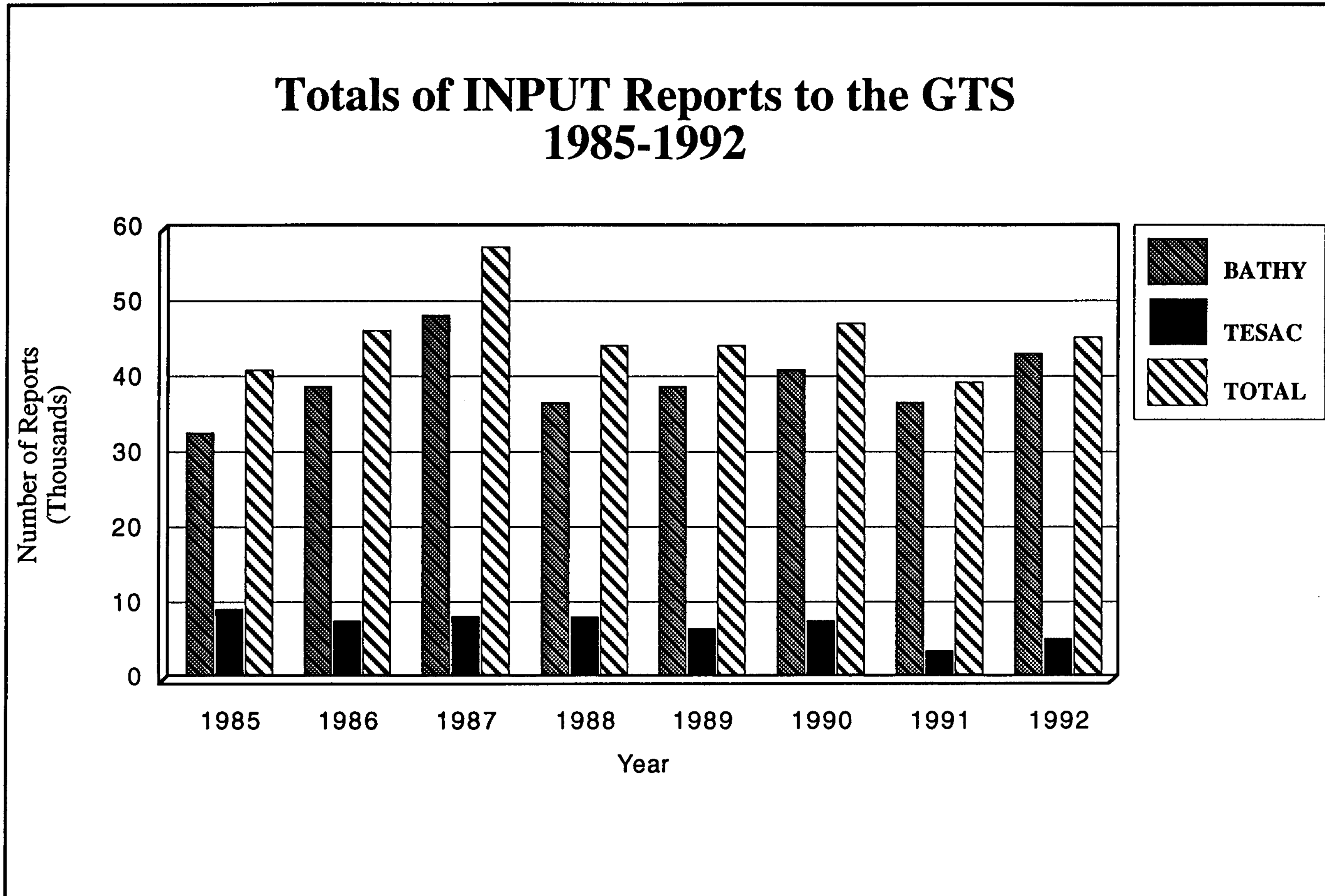



Figure AII-1. Numbers of BATHY and TESAC messages to the GTS during the period 1985–1992.

located in the tropical zone is considered as the TOGA sea-level network. A set of 65-70 GLOSS stations constitutes the WOCE array needed for support of satellite altimetry and for estimate of transport variations through straits.

The flow of sea-level data from the GLOSS network includes the following major streams:

a) Submission of monthly mean sea-level values to the Permanent Service for Mean Sea Level (PSMSL). Sea level data from 200 GLOSS stations are available at PSMSL (although for different time periods).
b) Submission of sea-level data on a real or near real-time basis to specialized international sea-level data analysis centers established within the framework of research programs and the IGOSS Sea Level Program in the Pacific. A total of 80 stations in the Pacific submit data in an operational mode to the specialized oceanographic center for the Pacific.
c) Final submission of sea-level data from the GLOSS network and specialized sea-level analysis centers and their archives to the World Data Centers (Oceanography).

The PSMSL, Proudman Oceanographic Laboratory, Bidston Observatory, established in 1933, is charged with the collection, dissemination, and analysis of mean sea-level data. The computer data bank holds series from over 1000 stations. A catalogue of all data held by PSMSL was published in 1987. The TOGA Sea Level Center, established in 1985 at the University of Hawaii, collects sea-level data in the form of hourly, daily, and monthly sea-level heights, in the TOGA area between 30°N and 30°S in the Pacific. The data set, updated annually, includes 971 station years through 1988 from 94 stations.

The Specialized Oceanographic Center (SOC) for the IGOSS Sea Level Program in the Pacific, established in 1984 at the University of Hawaii, collects data monthly from 78 Pacific sea level stations and prepares and disseminates sea-level products which are useful for scientific analysis of climate-related ocean processes.

## D. International Oceanographic Data and Information Exchange (IODE)

### 1. Functions.

The IODE system was established in 1960 to enhance marine research, exploration, and development by facilitating the exchange of oceanographic data and information among participating Member States of IOC. IODE data exchange is non-operational (delayed mode), although data exchanged under IGOSS are also eventually transferred into IODE.

The fundamental principle of the IODE system is that national institutions, international programs, and individual scientists contribute data voluntarily to the data centers of the IODE system for the benefit of all. Users of the IODE system can then obtain free of charge or at a very low price data, data products, or data inventory information. Responsibilities of IODE data centers are described in IOC Manuals on IODE. Data exchanged internationally are those collected by national programs, international cooperative expeditions and programs, and other oceanographic programs of international interest.

### 2. Organization.

The IODE network includes the following elements:

a) National Oceanographic Data Centers (NODCs) / Designated National Agencies (DNAs). NODCs provide the contact with the oceanographic programs in a Member State and from those programs compile the data and make it available for exchange. In addition to the responsibilities for data collection, processing, quality control, archiving, and dissemination of data nationally according to national procedures, the NODCs are charged with the responsibility for conducting international exchange.

b) Responsible National Oceanographic Data Centers (RNODCs). The RNODC scheme was developed to enable the international exchange system to accommodate the increasing variety and volume of data being collected. The RNODC is a national center responsible for assisting the WDCs. This assistance may be provided directly to the WDCs in support of their mission, directly to other Member States to assist them with particular requirements for data provision or retrieval, or to an international scientific program.

c) WDCs for Oceanography established within the ICSU WDC systems, are also recognized as part of the IODE system. Coordination of IOC and ICSU activities in this field is provided through close interaction between the IOC Committee on IODE and the ICSU WDC Panel. The WDCs for Oceanography receive oceanographic data and inventories from NODCs, RNODCs, marine science organizations, and individual scientists, freely exchange data, publications, and inventories between themselves and provide, upon request, copies of data, inventories, and publications to NODCs/DNAs, to RNODCs, and to international cooperative programs in exchange, of with a charge not to exceed the cost of provided the service.

Global ocean science programs have a strong incentive to develop their own data management schemes to serve their immediate objectives. Nevertheless, many data sets are or will be common to many of the programs. Many problems concerning data handling (e.g., formatting, quality control, data tracking) may also be common. There is a need for a central data coordination system to ensure proper coordination of environmental data flow, collection and archiving, their easy access to scientists and governments and to avoid duplication of efforts both on national and international levels.

As of 1988 the international marine data base system on the level of the WDCs, Oceanography, contained data for more than 2,250,000 observations. It includes data from more than 960,000 oceanographic stations, 505,000 bathy-thermographs, and 660,000 current measurements. The data available cover more than 17,000 research cruises and include data from various international programs. Sixty-one countries provided data to WDCs.

## ANNEX III: Enabling Technology Questionnaire

The OOSDP used its own knowledge and that of outside experts to develop a picture of possible technology for the ocean observing system for climate. The Panel also solicited input via a questionnaire distributed broadly to the international oceanographic community. A copy is reproduced below. About fifty responses were received. Because some respondents described more than one instrument system, the number of technologies represented is larger. Some respondents provided only comments. The list of respondents is provided in this annex, and each technical response is coded by a letter-number combination. These codes are included in Table VII.B.3-1 where applicable; not all instruments described in the questionnaire responses were deemed relevant for use in the ocean observing system for climate

### Questionnaire: Enabling Technologies for the Global Ocean Observing System

Complete one questionnaire for each instrument

Instrument ____________________________________________

Originator ____________________________________________

| | | | |
|---|---|---|---|
| Type: | ( ) Sensor | ( ) Platform | ( ) Telemetry |
| Complete: | 1.a | 1.b | 1.c |

1.a Sensor Specifications

For each parameter, list:

| Parameter Measured | Range | Resolution | Accuracy | Drift | Calibration Frequency | Sample Rate |
|---|---|---|---|---|---|---|
| ____________ | ____ | ______ | _____ | ____ | ______ | ____ |

1.b Platform Specifications

Type (mooring, drifter, float, autonomous vehicle, etc.)
Depth range
Power consumption
Compatible measurements
Longevity

1.c Telemetry Specifications

Type (Satellite, Acoustic, Undersea cable etc.)
Baud rate (active)
Duty Cycle
Monthly Baud rate (Megabytes/month)
Power consumption
Longevity

2. Operation: What training or special skills are required for use of this instrument?

3. Maintenance: What is required to maintain the instrument? (power consumption, supplies, etc.)

4. Post processing: What is required to convert raw measurement to desired variable? (additional measurements, field calibrations, etc.)

5. Cost:

   Present unit cost ______________________________

   Estimated cost if mass produced ____________________

   Estimate cost of redesign effort for mass production __________

6. Status:

   a. Existing ( )        Operational ( )        Research ( )

   b. In development ( )

      Estimated completion date ______________________

      Development costs __________________________

   c. Proposed ( )

      Agency ________________________________

      Required development time ____________________

      Development costs __________________________

7. Problems: Identify shortcomings of instrument for widespread, systematic use.

8. Application notes: Please provide any additional information you think relevant to the use of this instrument, especially with regard to its use in an operational (rather than research) mode.

9. Replacement technology: What alternative technology might better measure this parameter if developed?

10. References

## Respondents to Questionnaire on Enabling Technologies for GOOS

| | |
|---|---|
| A-1<br>AES<br>Bedford, Nova Scotia<br>CANADA | Nomad Buoy System |
| A-2<br>AMETEK<br>USA | Acoustic Doppler Current Profiler |
| A-3<br>Stuart J. Anderson<br>HF Radar Division<br>Surveillance Research Laboratory<br>Defense Science and Technology Organization<br>Adelaide, S.A. 5001<br>AUSTRALIA | HF Skywave Radar |
| A-4<br>Sebastian Archer<br>MIROS Limited<br>Ablgownie Technology Centre<br>Campus 3, Balgownie Drive<br>Bride of Don<br>Aberdeen AB22 8GW<br>SCOTLAND | Wave Radar |
| B-1<br>Richard Burt<br>Chelsea Instruments Ltd<br>2/3 Central Ave.<br>East Molesey<br>Surrey KT8 0QX<br>UNITED KINGDOM | 1. $pCO_2$<br>2. Chlorophyll Fluorometer<br>3. Nutrient Sensor |
| Lennart Bengtsson<br>Max Planck Institute for Meteorology<br>Bundesstr. 55<br>D-2000 Hamburg 13<br>GERMANY | (Comments only) |
| Mike Bewers<br>Bedford Institute of Oceanography<br>P.O. Box 1006<br>Dartmouth, Nova Scotia B2Y 4A2<br>CANADA | (Comments only) |
| B-2<br>Albert M. Bradley<br>Advanced Engineering Laboratory<br>Woods Hole Oceanographic Institution<br>Woods Hole, MA 02543 | Fast Hydrographic Profiler |

B-3
Neil Brown — Acoustic Current Meter
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

C-1
Etienne Charpentier — Drifting Buoys
Technical Coordinator of the
WMO-IOC Drifting Buoy Cooperation Panel

C-2
Alan Chave — Horizontal Electrometer
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

C-3
Ong Tiong Cheong — Gas Production Platforms
Malaysian Meteorological Service
Jalan Sultan
46667 Petaling Jaya
MALAYSIA

C-4
Earl F. Childress — Data Logger
Pacer Systems, Inc.
900 Technology Park Dr.
Billerica, MA 01821

C-5
P. G. Collar — Autosub
Natural Environment Research Council
Institute of Oceanographic Sciences
Deacon Laboratory
Brook Road, Wormley
Godalming, Surrey GU8 SUB
UNITED KINGDOM

C-6
LeRoy W. Collins, Jr.
COMSAT/Maritime Services
950 L'Enfant Plaza, SW
Washington, DC 20024

C-7
C. Contralmirante — Current Meter Moorings
S.I.O. Mexico

D-1
Michael D. DeGrandpre — $pCO_2$ Sensor
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

D-2
Jean-Guy Dessureault
Dept. of Fisheries & Oceans
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2
CANADA

Moving Vessel CTD

D-3
Tom Dickey
Dept. of Geological Sciences
University of Southern California
3651 Truesdale Parkway
Science Bldg. Rm. 117
Los Angeles, CA 90089-0740

1. Beam Transmissometer
2. Stimulated Fluorometer
3. Current Meter
4. Natural Fluorometer
5. Scalar Irradiance
6. Spectral Irradiance

D-4
F.A. Dongen
Director
The Oceanographic Company
of the Netherlands
Rotterdamseweg 185
P.O. Box 177
2600 MH Delft
THE NETHERLANDS

Users of sensors for:
1. Air Pressure
2. Nutrients
3. Radioactivity
4. Temperature Chain
5. Wind Speed/Direction
6. Air Temperature
7. Surface Waves
8. Oxygen
9. Currents

F-1
Daniel Frye
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Moored Vertical Profiler

F-2
Arnold Furlong
Brooke Ocean Technology Limited
Bedford Institute of Oceanography
PO Box 2220
East Dartmouth, Nova Scotia
CANADA B2W 3Y2

1. Moving Vessel CTD
2. Moored Ocean Profiler
3. Programmable Diving Buoy

G-1
John Gamble
The Sir Alister Hardy Foundation
for Ocean Science
c/o Plymouth Marine Laboratory,
Prospect Place, The Hoe, Plymouth
P11 3DH UNITED KINGDOM

1. Continuous Plankton Recorder
2. Undulating Oceanographic Recorder

G-2
Philippe Gaspar
ARGOS/CLS
18, Avenue Edouard-Belin
31055 Toulouse Cedex
FRANCE

Altimeter

G-3
Michael Gregg
Applied Physics Lab
University of Washington
1013 NE 40th Street
Seattle, WA 98105

Mixing Measurements

G-4
Trygve Gytre
Institute of Marine Research
P.O. Box 1870/72
N-5024 Bergen, NORWAY

1. Mini Current Meter
2. Mini STD

H-1
Dave Hosom
Woods Hole Oceanographic Institutions
Woods Hole, MA 02543

Improved Meteorology (IMET) System

J-1
Peter Jones
Bedford Institute of Oceanography
P. O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2
CANADA

Marine Chemistry
(Comments Only)

K-1
Arata Kaneko
Hiroshima University
Department of Environmental Sciences
1-4 Kagamiyama, Higashi-Hiroshima
Hiroshima 724, JAPAN

ADCP on VOS

K-2
Junzo Kasahara
Earthquake Research Institute
University of Tokyo
1,1,1 Yayoi, Bunkyo
Tokyo 113, JAPAN

Cabled Seismometers with
ancillary measurements

K-3
V. Kogan
27A Komsomolskaya St.
14 Apartment
690002 Vladivostok
RUSSIA

Doppler Profiler Mooring

L-1
C. Langdon
Lamont-Doherty Earth Observatory
Palisades, NY 10964

Pulsed Oxygen Sensor

L-2
Jim Larsen
Pacific Marine Environmental Laboratory/NOAA
7600 Sand Point Way N.E.
Seattle, WA 98115

Cross-stream Voltages

M-1
M. Maccio, J. Marra
Lamont-Doherty Earth Observatory
Palisades, NY 10964

Spectro-Radiometer

M-2
M.S. McCartney
Proudman Oceanographic Laboratory
Birkenhead
Merseyside L43 7PA
UNITED KINGDOM

1. Deep Sea Pressure Recorder
2. Deep Sea Inverted Echo Sounder
3. Coastal Sea Level Network
4. Island Sea Level Gauge

M-3
Hugh Milburn
Pacific Marine Environmental Laboratory
NOAA Building Number 3
7600 Sand Point Way N.E.
Seattle, WA 98115

1. Sea-cables for transport
2. Bottom Pressure
3. Rumbleometer
4. Acoustic Ambient Noise
5. Chemical Scanner
6. PROTEUS Mooring
7. Atlas Mooring
8. Acoustic Extensometer
9. Miniature T/P Recorder

M-4
Vincent Mourier
Tekelec Systems
29 Avenue de la Baltique
91953 Les Ulis Cedex
FRANCE

Subsurface Floats

P-1
Richard Phelps
Conrad Blucher Institute
for Surveying and Science
Corpus Christi State University
6300 Ocean Drive
Corpus Christi, TX 78412

Water Properties/Water Level

| | |
|---|---|
| R-1<br>Michael Reynolds<br>Dept. of Applied Sciences<br>Brookhaven National Laboratory<br>Bldg. 318<br>Upton, NY 11973 | Atmospheric Radiation Measurements |
| R-2<br>P. Richardson<br>Woods Hole Oceanographic Institution<br>Woods Hole, MA 02543 | Autonomous Profilers<br>(Slocum profiler and glider) |
| S-1<br>Tom Sanford<br>Applied Physics Laboratory<br>University of Washington<br>1013 NE 40th Street<br>Seattle, WA 98105 | 1. Absolute Velocity Profiler<br>2. Expendable Velocity Profiler<br>3. EM Cables<br>4. Moored Electric Field Sensor<br>5. Electric Field Float<br>6. Towed Transport Meter<br>7. EM Surface Drifter |
| S-2<br>Gary Sharp<br>Cooperative Institute for Research<br>in the Integrated Ocean Sciences<br>2560 Garden Road<br>Monterey, CA 93940 | High Seas Fisheries Fleets |
| S-3<br>Edward Sholkovitz<br>Woods Hole Oceanographic Institution<br>Woods Hole, MA 02543 | Precipitation Chemistry |
| Robert Stewart<br>College of Geosciences & Maritime Studies<br>Texas A&M University<br>College Station, TX 77843-3146 | Comments Only |
| T-1<br>A. Tolkachev<br>IOC, UNESCO<br>1 rue Miollis<br>75732 Paris Cedex 15<br>FRANCE | IOC Sea Surface Topography |
| T-2<br>John Toole<br>Woods Hole Oceanographic Institution<br>Woods Hole, MA 02543 | Moored Vertical Profiler |
| T-3<br>TSKA<br>828 Mills Pl.<br>North Bend, WA 98045 | Remote Wave Height Meter |

W-1
Richard Worsfold
Institute for Space & Terrestrial Science
4850 Keele St.
North York, Ontario
M3J 3K1 CANADA

Sea Ice/Remote Sensing

Z-1
Vince Zegowitz
National Weather Service
NOAA
Silver Spring, MD 20910

Marine Observations Program

## ANNEX IV: Acronyms Used in Report

ACC..............................Antarctic Circumpolar Current
ACSYS .........................Arctic Climate System Study
ADCP............................Acoustic Doppler Current Profiler
ADEOS ..........................Advanced Earth Observing Satellite (Japanese)
AIW .............................Arctic Intermediate Water
ALACE..........................Autonomous Lagrangian Circulation Explorer
ARM ............................Atmospheric Radiation Measurement program
ATLAS ..........................Autonomous Temperature Line Acquisition System
ATOC............................Acoustic Thermometry of Ocean Climate
ATSR............................Along-Track Scanning Radiometer
AUV .............................Autonomous Underwater Vehicle
AVHRR .........................Advanced Very High Resolution Radiometer
BMRC...........................Bureau of Meteorology Research Centre (Australia)
CalCOFI.........................California Cooperative Fisheries Investigation
CBOS ...........................Commission for Basic Ocean Systems
CBS..............................Commission for Basic Systems
CCCM ...........................Commission for Ocean Chemistry Monitoring
CCCO............................Committee on Climatic Changes and the Ocean
CDW ............................Circumpolar Deep Water
CEOS............................Committee on Earth Observing Systems
CLIVAR.........................Climate Variability and Predictability Research Programme
CMM ............................Commission for Marine Meteorology
COADS..........................Comprehensive Ocean Atmosphere Data Set
COCM ...........................Commissions for global Ocean Chemistry Monitoring
CPR..............................Continuous Plankton Recorder
CTD..............................Conductivity-Temperature-Depth probe
CUOM ..........................Commission for Upper Ocean Measurements
CZCS............................Coastal Zone Color Scanner
DAC..............................Data Assembly Centers
DIU ..............................Data Information Unit
DMSP...........................Defense Meteorological Satellite Program
ECMWF.........................European Centre for Medium-range Weather Forecasts
ENSO............................El Niño / Southern Oscillation
EOF..............................Empirical Orthogonal Function
EPOCS ..........................Equatorial Pacific Ocean Climate Studies
ERL..............................Environmental Research Laboratories
ERS-1............................Remote Sensing Satellite (ESA)-1
ESMR............................Electronic Scanning Microwave Radiometer
FHP..............................Fast Hydrographic Profiler
ftp ...............................file transfer protocol
GCM.............................General Circulation Model
GCOS............................Global Climate Observing System
GEK .............................Geomagnetic Electrokinetograph
Geosat ...........................Navy Geodetic Satellite
GEOSECS ......................Geochemical Ocean Section Study
GEWEX.........................Global Energy and Water Cycle Experiment
GLOSS ..........................Global Sea-Level Observing System
GOOS...........................Global Ocean Observing System
GPCP............................Global Precipitation Climatology Project (WCRP)
GPS..............................Global Positioning System
GTS..............................Global Telecommunication System
GTSPP ..........................Global Temperature and Salinity Plot Project

HIRS ............................High-Resolution Infrared Sounder
HOOP ............................Health of the Ocean Panel
HRC ............................Highly Reflective Cloud
I-GOOS ............................Intergovernmental Committee for GOOS
ICSU ............................International Council of Scientific Unions
IGBP ............................International Geosphere-Biosphere Program
IGOSS ............................Integrated Global Ocean Services System
IGY ............................International Geophysical Year
IOC ............................Intergovernmental Oceanographic Commission
IODE ............................International Oceanographic Data and Information Exchange
IPCC ............................Intergovernmental Panel on Climate Change
ISCCP ............................International Satellite Cloud Climatology Project
ITCZ ............................Intertropical Convergence Zone
IUSS ............................Integrated Undersea Surveillance System
J-GOOS ............................Joint Scientific and Technical Committee for GOOS
JGOFS ............................Joint Global Ocean Flux Study
JIC ............................Joint Ice Center
JMA ............................Japan Meteorological Agency
JSC ............................Joint Scientific Committee
LSDW ............................Labrador Sea Deep Water
MCSST ............................Multi-Channel Sea Surface Temperature
MIMR ............................Multifrequency Imaging Microwave Radiometer
MODIS ............................Moderate-Resolution Imaging Spectrometer
NADW ............................North Atlantic Deep Water
NCAR ............................National Center for Atmospheric Research
NCDC ............................National Climate Data Center
NDBC ............................National Data Buoy Center
NESDIS ............................National Environmental Satellite, Data and Information Service
NMC ............................National Meteorological Center (NOAA)
NOAA ............................National Oceanic and Atmospheric Administration
NODC ............................National Oceanic Data Center
NOS ............................National Ocean Service
NSCAT ............................NASA Scatterometer
NWP ............................Numerical Weather Prediction
OCTS ............................Ocean Color and Temperature Sensor
OLR ............................Outgoing Longwave Radiation
OOPC ............................Ocean Observing Panel for Climate
OOSDP ............................Ocean Observing System Development Panel
OWS ............................Ocean Weather Stations
PIR ............................Precision Infrared Radiometers
PMEL ............................Pacific Marine Environmental Laboratory
PROTEUS ............................Profile Telemetry of Upper Ocean Currents
PSP ............................Precision Spectral Pyranometers
PW ............................Petawatts ($10^{15}$ watts)
RAFOS ............................SOFAR spelled backwards
SAR ............................Synthetic Aperture Radar
SCOR ............................Scientific Committee on Oceanic Research
SCPP ............................Seasonal-to-interannual Climate Prediction Program
SeaWiFS ............................Sea-Viewing Wide Field Sensor
SH ............................Southern Hemisphere
SLP ............................Sea Level Pressure
SMMR ............................Scanning Multi-channel Microwave Radiometer
SOFAR ............................Sound Fixing and Ranging float
SOOP ............................Ship of Opportunity Program

SPCZ ............................South Pacific Convergence Zone
SSM/I ............................Special Sensor Microwave/Imager
SSS ...............................Sea Surface Salinity
SST ...............................Sea Surface Temperature
STCZ ............................SubTropical Convergence Zone
TAO ...............................Tropical Atmosphere Ocean
TIROS ...........................Television Infrared Observing Satellite
TOGA ............................Tropical Ocean and Global Atmosphere Program
TOGA-COARE .................TOGA's Coupled Ocean-Atmosphere Response Experiment
TOPEX/POSEIDON ...........Ocean Topography Experiment/Altimetry Research in
TOVS ............................TIROS Operational Vertical Sounder
TRANSPAC ....................Trans-Pacific Experiment
TRMM ...........................Tropical Rainfall Measuring Mission
TWXXPPC .....................TOGA/WOCE XBT/XCTD Programme Planning Committee
U.S ...............................United States
UK ................................United Kingdom
VLBI .............................Very-Long Baseline Interferometry
VOS ..............................Volunteer Observing Ship
VSOP-NA .......................VOS Special Observing Project-North Atlantic
WCRP ...........................World Climate Research Program
WDC .............................World Data Centers
WHOI ............................Woods Hole Oceanographic Institution
WHP .............................WOCE Hydrographic Program
WMO .............................World Meteorological Organization
WOCE ...........................World Ocean Circulation Experiment
WOTAN .........................Weather Observations Through Ambient Noise
WWW ...........................World Weather Watch
XBT ..............................eXpendable BathyThermograph probe
XCTD ............................eXpendable Conductivity-Temperature-Depth probe